# APPENDIX F

# REVIEW OF CONDITION ASSESSMENT TOOLS AND TECHNIQUES

## Introduction

This Appendix presents summary reviews of 85 condition assessment tools and techniques identified during the research.

As noted in Chapter 1 - Introduction of the report, a first pass assessment of the tools and techniques used for condition and performance assessment in various sectors was made in Phase 1 of the project. This was achieved through a review of literature and other information sources relating to asset management and condition assessment tools and techniques. Draft summaries of relevant tools were written and incorporated into the preliminary report.

The summaries were then sent out to a range of industry professionals for peer review during Phase 2 of the project. A data collection spreadsheet that detailed all of the tools and techniques identified in the project was also sent to each reviewer. The reviewers were asked to use the spreadsheet to confirm the applicability of tools included on the list and to add any additional tools that were used by or known to them.

The scope of this peer review exercise was entirely dependent on the goodwill of the reviewers. Given this fact, the response was considerable, and the project team would like to acknowledge the kind assistance of the following individuals:

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# F1.0 Acoustic Emission

## F1.1 Overview

Acoustic emissions are transient elastic waves that are generated by the rapid release of strain energy from within a material. A common source of acoustic emission is the sudden appearance or propagation of a microscopic crack within a material under load.

Material defects such as cracks, pits and gas bubbles act as local stress concentrators that promote crack propagation. Acoustic emissions indicate the presence of these material defects. Frequent acoustic emissions are an indication that there are numerous points of high stress concentration, and that the material is approaching failure. Other sources of acoustic emission that do not involve material failure include active corrosion, cavitation of pumps, de-lamination of a composite material, turbulent flow through a leak in a pressure vessel and phase transformation of a monolithic material.

Acoustic emissions can be detected by a sensor and recorded. In this way, acoustic emission monitoring can be used as a non-destructive method of condition monitoring. The frequency of acoustic emissions can be increased by placing a structure under a higher than normal stress (load). Acoustic emission testing can thus be used to gather additional information where a structure is tested under high loads for another reason, for example, factory acceptance testing of pressure vessels.

## F1.2 Main Principles

Acoustic emission testing is different to ultrasound testing (see reviews of ultrasonic techniques for more information), which involves sending an ultrasound signal into a material and measuring any echoes produced. In contrast, acoustic emission testing involves measuring the signals that are generated from within the material itself. Each acoustic emission is a unique real-time event, for example, caused by a crack expanding and cannot be exactly repeated. Acoustic emission instrumentation typically includes the following items:

- A sensor.
- A preamplifier and/or a postamplifier.
- Signal processing electronics for feature extraction and waveform capture.
- A microprocessor and a digital signal processor.
- Acoustic emission analysis software.

An acoustic emission sensor is a transducer, typically constructed of a piezoelectric material. Most sensors measure in the ultrasonic frequency range between 20 kHz and 1 MHz. However, sensors outside this range are commercially available. Strongly attenuating materials, such as concrete and masonry, are monitored at lower frequencies while metals, polymers and composite structures are monitored at higher frequencies. Acoustic emission sensors typically have a diameter and depth of approximately one inch. The sensors can be attached to the material or structure under analysis using either magnetic hold-downs, a couplant layer or thick glue.

Since the output voltage of an acoustic emission sensor is very small, a preamplifier or a postamplifier should be connected to the sensor output. The amplifier output should be connected to signal processing equipment, typically a computer with the relevant software or a purpose-built hand held instrument for acoustic emission testing.

The intensity of an acoustic emission event will decrease as the distance from the source increases. By setting up several sensors on the structure and by knowing the attenuation properties of the material, the location of the acoustic emission source can be determined.

## F1.3 Application

Acoustic emission testing is most commonly used for detecting and locating material defects in pressure vessels, storage tanks, pipes, heat exchanges, aerial lift devices and welded joints.

Many other applications for acoustic emission testing are currently being researched and developed. One example is the local, long-term monitoring of civil engineering structures such as bridges and pipelines. Acoustic emission testing of glass-fiber reinforced parts, such as fan blades, is also becoming more common.

A number of standards reference this technique for a variety of products ranging from small parts to pressure vessels.

- ASTM-E1067-96, ASTM-E1106-86(1992)e1, ASTM-E1118-95, ASTM-E1139-97, ASTM-E1211-97, ASTM-E1419-96, ASTM-E1781-98, ASTM-E1888-97, ASTM-E1930-97, ASTM-E1932-97, ASTM-E569-97, ASTM-E650-97, ASTM-E749-96, ASTM-E750-98, ASTM-E751-96, ASTM-E976-98, ASTM-F1430-98, ASTM-F1797-98, ASTM-F914-98.
- AAR Procedure for AE Evaluation of Tank Cars and IM101 Tanks.
- ASME V, Article 12, Acoustic Emission Examination of Metallic Vessels During Pressure Testing.
- SPI Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Resin (RP) Tanks/Vessels.

## F1.4 Practical Considerations

- A trained operator is required to carry out acoustic emission inspections.
- The equipment is commercially available.
- In many applications, acoustic emission testing requires that a load be put on the asset. For piping and tanks this is normally achieved by over pressurization by 10%.

## F1.5 Advantages

- The ability to observe the creation and growth of material defects within a material over the entire load history of the structure (with permanently placed sensors).
- Testing does not need to disturb the structure/specimen.

## F1.6 Limitations

- Only qualitative estimates of material damage and failure predictions are possible.
- Environments are often noisy and the acoustic emission signals are weak so distinguishing noise from the measurements can be difficult.

**Table F-1. Summary Acoustic Emission.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, aerial lift devices, pressure vessels, storage tanks. |
| | Material | Concrete, masonry, metals, polymers, composites. |
| | Service area | Potable and wastewater. |
| | Access requirements | None. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Continuous in time and space. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Tests can be undertaken while the asset is on-line. |
| Technical suitability | Assessment parameters | Material defects. |
| | Integration with software tools | Acoustic emission remote monitoring equipment is commercially available. |
| | Commercialization of tool | Commercially available acoustic emission equipment is readily available from a limited number of suppliers. |
| | Previous/existing use of the tool in sector | Widely used in other sectors. |
| | Accuracy/reliability | Qualitative estimates. |
| | Ease of validation of results | Only through further inspection of components. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | A trained operator is required. Training and certification courses are commercially available. |
| | Technology required (level of tool sophistication) | A straightforward acoustic emission instrument hardware design includes a transducer, preamplifier, bandpass filter, amplifier and several digital signal processors. |
| | Documentation | Refer to the Standards listed. |
| | Availability of technical support | Commercially available. |
| Economic factors | Cost per inspection | Depends on application. |
| | Resource requirements | Depends on application. |

## F1.7 Bibliography


1. AAR Procedure for AE Evaluation of Tank Cars and IM101 Tanks
2. ASME V, Article 12, Acoustic Emission Examination of Metallic Vessels During Pressure Testing
3. ASTM-E1067-96 Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels
4. ASTM-E1106-86(1992)e1 Standard Method for Primary Calibration of Acoustic Emission Sensors
5. ASTM-E1118-95 Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP)

6. ASTM-E1139-97 Standard Practice for Continuous Monitoring of Acoustic Emission from Metal Pressure Boundaries
7. ASTM-E1211-97 Standard Practice for Leak Detection and Location Using Surface-Mounted Acoustic Emission Sensors
8. ASTM-E1419-96 Standard Test Method (STM) for Examination of Seamless, Gas- Filled, Pressure Vessels Using Acoustic Emission
9. ASTM-E1781-98 Standard Practice for Secondary Calibration of Acoustic Emission Sensors
10. ASTM-E1888-97 STM for Acoustic Emission Testing of Pressurized Containers Made of Fiberglass Reinforced Plastic with Balsa Wood Cores
11. ASTM-E1930-97 STM for Examination of Liquid Filled Atmospheric and Low Pressure Metal Storage Tanks Using Acoustic Emission
12. ASTM-E1932-97 Standard Guide for Acoustic Emission Examination of Small Parts
13. ASTM-E569-97 Standard Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation
14. ASTM-E650-97 Standard Guide for Mounting Piezoelectric Acoustic Emission Sensors
15. ASTM-E749-96 Standard Practice for Acoustic Emission Monitoring During Continuous Welding
16. ASTM-E750-98 Standard Practice for Characterizing Acoustic Emission Instrumentation
17. ASTM-E751-96 Standard Practice for Acoustic Emission Monitoring During Resistance Spot-Welding
18. ASTM-E976-98 Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response
19. ASTM-F1430-98 STM for Acoustic Emission Testing of Insulated Aerial Personnel Devices with Supplemental Load Handling Attachments
20. ASTM-F1797-98 STM for Acoustic Emission Testing of Insulated Digger Derricks
21. ASTM-F914-98 STM for Acoustic Emission for Insulated Aerial Personnel Devices
22. SPI Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Resin (RP) Tanks/Vessels

## F2.0 Active Acoustic Inspection

### F2.1 Overview

This non-destructive technique uses the transmission of sound to assess defects in the structure of pipes; generally of cementituous materials. A known force is imparted to the asset and sensors measure the response. Cracks, delamination and other discontinuities affect the transmission of sound. Generally damaged pipes will display lower wave speeds and propagate less energy to the sensors. Depending on the response, the assessor can thus identify if the asset has cracks and other defects.

### F2.2 Main Principles

The active acoustic inspection tool consists of a means of imparting sound energy and sensors to detect that energy.

An impact, generally from a steel ball, is used to impart sound energy which propagates along the asset's length. Sensors are placed to detect the sound propagated. Assets with defects such as crack or voids will experience some reflection of the sound reducing the energy that reaches the sensors.

### F2.3 Application

Active acoustic inspection is applied to cementituous pipes to identify cracks, delamination, or other defects. It can be used to assess wire breaks, delamination and cracks in pre-stressed cylinder concrete pipe (PCCPs).

- No ASTM or ISO standards were identified for this application.

### F2.4 Practical considerations

- The technique is also known as seismic pulse echo.
- Active acoustic inspection is widely used in many industries for inspecting concrete assets. As such it is fully commercialized. This method relies heavily on operator skill, but is probably the most commonly used NDE inspection technique used for cementituous pipes.
- The tools are portable and the approach relatively easy to use. The output is a qualitative assessment indicating the presence of pipe defects.
- Manual inspection is most sensitive to defects near the inside diameter, and prone to missing defects near the outside diameter of the pipe. This is a problem for inspecting PCCPs, but is especially problematic when inspecting pre-cast, post-tensioned pipe, as a common failure mechanism in this pipe type is failure of the tensioning metal by outside diameter corrosion, and this damage is difficult to detect manually.
- Both inside diameter and outside diameter defects can be more readily detected using instrumented testing.
- The asset must be exposed prior to inspection to allow access to points on the pipe surface. Pipe assets can be inspected internally using man entry techniques.
- The pipe should also be dewatered prior to inspection as the water will alter the sound propagation properties.

### F2.5 Advantages

- This technique can be conducted quickly with results immediately available.

- The results of this technique give information about the overall condition of the pipe.

## F2.6 Limitations

- Pipe assets must be dewatered before inspection.
- Asset must be exposed prior to inspection. However, full exposure of the asset is not required; exposure only need allow access to points on pipe surface.
- This technique may not locate specific small defects).

**Table F-2. Summary Active Acoustic Inspection.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipe assets. |
| | Material type | Cementituous, PCCPs |
| | Service area | Potable and wastewater. |
| | Access requirements | Access to asset surface is required. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None (man entry for pipes). |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Non-destructive test. |
| | Interruption to supply/function | Inspection conducted while pipe is off-line and dewatered. |
| Technical suitability | Assessment parameters | Presence of defects. |
| | Integration with software tools | None. |
| | Commercialization of tool | Approach is widely used and available from numerous suppliers. |
| | Previous/existing use of the tool in sector | Widely used in civil industries. |
| | Accuracy/reliability | Qualitative measure. |
| | Ease of validation of results | Results validated by exhumation of pipe. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Training in tool use required. |
| | Technology required (level of tool sophistication) | Can be instrumented or manual. |
| | Documentation | Supplied with tool, no standards identified. |
| | Availability of technical support | From suppliers. |
| Economic factors | Cost per inspection | Relatively low. |
| | Resource requirements | Man power sufficient to expose asset and for confined spaces when applicable. |

## F2.7 Bibliography


1. Dingus, M., Haven, J. and Austin, R. *Nondestructive None Invasive Assessment of Underground Pipes*, AwwaRF, USA, 2002
2. Makar, J. M. ; Chagnon, N. *Inspecting systems for leaks, pits, and corrosion*, National Research Council of Canada, Institute for Research in Construction, NRCC-42802, 1999 (downloaded from www.nrc.ca/irc/ircpubs)
3. Lillie, K., Reed, C. and Rodgers, M. A. R., 2004, Workshop on Condition Assessment Inspection Devices for Water Transmission Mains, AwwaRF, USA, 2004

# F3.0 Air Permeability

## F3.1 Overview

Air permeability is a non-destructive test that can be used to determine the permeability and quality class of concrete. Concrete permeability is an excellent measure of the resistance of concrete against aggressive media. The ingress of water and air into the concrete can cause corrosion of steel reinforcement, which leads to a deterioration in the durability of the concrete. Air permeability testing is also referred to as 'gas' permeability testing.

There are two main methods for testing air permeability: the Torrent method, which measures the reduction of an applied vacuum over time, and the Cembureau method for oxygen permeability. The Torrent method is described here due to its more extensive use as a concrete durability assessment tool, and its widespread use on road, bridge and tunnel assets.

## F3.2 Main Principles

The Torrent method involves creating a vacuum at the surface of the concrete and monitoring the rate at which the pressure in the test chamber increases after the vacuum pump has been disconnected. The distinctive features of the method are a double chamber cell and a pressure regulator that balances the pressure in both chambers during the test. A microprocessor processes and stores test results.

The vacuum cell (Figure F-1) is held against the concrete surface by a vacuum. It has an inner circular chamber surrounded by an outer annular chamber. The outer chamber forces the air inflow to the inner chamber to be virtually uniaxial. A membrane pressure regulator brings the inner cell to a standard vacuum and is then turned off. The reduction in vacuum is measured over a time period. The permeability coefficient kT and the depth of penetration of the vacuum are calculated on the basis of a simple theoretical model and the permeability of the concrete is determined.

In the case of dry concrete, the quality class of the concrete cover can be read from a table using the kT value. In the case of moist concrete, kT is combined with the electrical concrete resistance *p* (rho) and the quality class is determined from a numerical relationship.

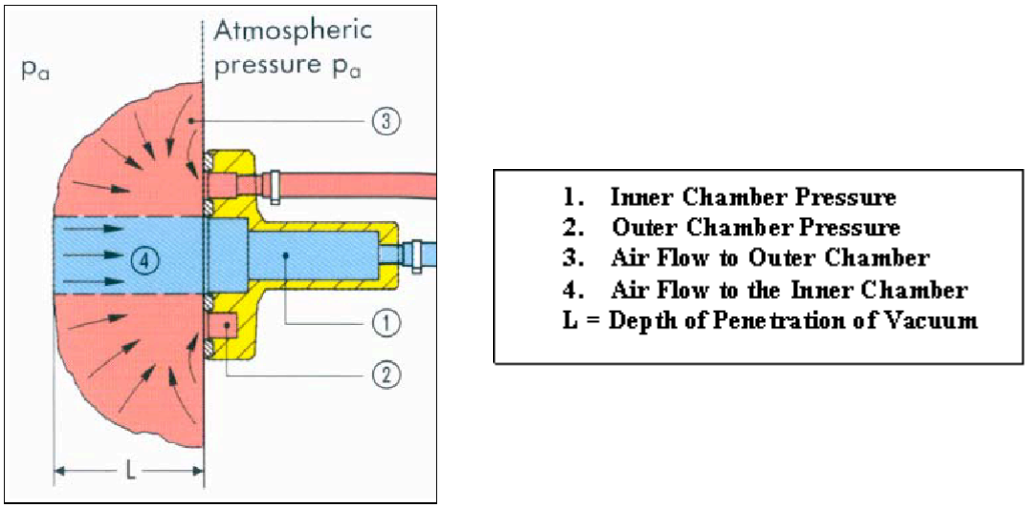


**Figure F-1. Torrent Permeability Tester (Mastrad, 2006).**

## F3.3 Application

Air permeability testing can be conducted on any concrete structure, including but not limited to; buildings, tanks, slabs and other such structures.

Standards which reference this test method are:

- DIN 28400 'Vacuum Technique' Deutsches Institut fur Normung (DIN)
- C497-05 Standard Test Methods for Concrete Pipe, Manhole Sections, or Tile
- ASTM C204-05 Standard Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus

## F3.4 Practical Considerations

- Instrumentation for carrying out air permeability testing is widely available from a number of commercial providers.
- The instrumentation is portable and does not require specialist skills to use. Individual tests can be completed in less than five minutes and the results are reproducible.
- Air permeability testing has been widely applied throughout both the water and other industry sectors for evaluating the durability of concrete.
- When testing is conducted on moist concrete, it should be complemented with the non-destructive determination of the electrical resistivity.

## F3.5 Advantages

- The testing method is suitable for both laboratory and onsite application. Testing is non-destructive and allows a rapid and reliable comparison between laboratory samples and site concrete.
- Measurements taken in the field are usually in good agreement with laboratory methods such as oxygen permeability, capillary suction, chloride penetration.
- Capillary suction can also be estimated from permeability results obtained from testing. Capillary suction is known to be related to permeability if the surface tension effects are not disturbed by water repellents.

## F3.6 Limitations

- The concrete needs to be dry for accurate testing, as permeability times are influenced by the moisture content of the concrete.
- When concrete is moist, air permeability values are significantly lower than when it is dry. This can result in a distortion in the evaluation of the quality of the concrete, particularly when it is performed in-situ.

**Table F-3. Summary Air Permeability.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Concrete elements with a flat surface such as slabs, beams, columns, walls and pavements |
| | Material type | Coated and uncoated concrete. |
| | Service area | Potable and wastewater. |
| | Access requirements | Direct contact with surface of asset. If asset is buried then it must be exposed. Surface coatings need to be removed in order to test permeability of concrete. Sufficient room is required for an operator where an asset has been exposed for testing. |
| | Limitations relating to asset condition | Concrete surface must be level and not be too porous or rough as the chambers of the vacuum cell need to seal effectively against the surface. |
| | Limitations relating to asset size/geometry | No limitations relating to size of concrete element. Surface must be flat. |
| | Continuous/discrete | Discrete reading. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | The asset can remain in use and does not need to be taken off-line. |
| Technical suitability | Assessment parameters | Permeability, quality class and capillary suction of concrete. |
| | Integration with software tools | Compatible with a RS 232 data interface gives a printout of measured objects and can be transferred to PC with MS Hyperterminal. |
| | Commercialization of tool | Equipment is fully developed, available from selected commercial vendors. |
| | Previous/existing use of the tool in sector | Widespread use internationally on bridges, road, and tunnel infrastructure. Limited application in the water industry. |
| | Accuracy/reliability | Accuracy better than 3% variation from reading. |
| | Ease of validation of results | Results are easily validated by conducting other standard tests for permeability such as ASTM C 1202. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy to use by following simple procedure. Unqualified staff can take measurements. |
| | Technology required (level of tool sophistication) | Apparatus comes in a digital version, which calculates and displays permeability. Quality class of concrete, capillary suction and carbonation depth of concrete can be estimated using supporting software by exporting data. The data from up to 200 tests can be stored and downloaded. |
| | Documentation | DIN 28400 Vacuum Technology. |
| | Availability of technical support | Technical support available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | Resources required depend on asset being inspected. Buried assets need to be exposed and surface cleaned and made smooth to ensure a seal with vacuum cell. |

## F3.7 Bibliography


1. Torrent, R. *The gas permeability of high-performance concretes: site and laboratory tests*. ACI Special Publication 186. pp1-4, 1999
2. Papworths, *Corrosion Monitoring Equipment, 'TORRENT Water Permeability' 'Defelsko Positest CarbonationTester for Concrete and Metal*. Papworths Pty Ltd Concrete Consultancy Service and NDT Equipment. 2005
3. DIN 28400 Vacuum Technology
4. C497-05 Standard Test Methods for Concrete Pipe, Manhole Sections, or Tile
5. ASTM C204-05 Standard Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus
6. Mastrad, http://www.mastrad.com/torrent.htm, accessed 2006

# F4.0 AQUA-Selekt

## F4.1 Overview

AQUA-Selekt is a software package developed in Germany, designed to assist infrastructure managers forecast sewer condition using representative CCTV inspection data (see CCTV Visual Inspection review). A qualitative condition inspection of a representative sample is first assessed. This data is then used to forecast the condition of sewers that are not inspected.

## F4.2 Main Principles

AQUA-Selekt is a PC based software tool that is used to determine the condition of assets within a sewerage network. The approach used is to infer the condition of the asset stock from the known condition of a representative sample of assets.

The CCTV inspection strategy used is dependent on the size of the network, requiring 10-20% of the network to be inspected. As the size of the network increases, the percentage inspection required decreases.

The condition of the inspected sample is used to extrapolate the condition trend of the sewers that have not been inspected by means of statistical evaluation.

## F4.3 Application

AQUA-Selekt is designed to assist with the forecasting of sewer condition using representative CCTV-inspection data.

- The selection strategy used by AQUA-Selekt is in accordance with DIN EN 752-5.

## F4.4 Practical considerations

- The software is readily available, commercialized, and used by several European authorities with a handful of users in other areas. It uses a Windows Explorer-style navigation structure.
- The method has been successfully tested in Germany on the sewer systems at Volkswagen plants in Wolfsburg, Emden and Brunswick, and is currently being developed further within the scope of a research project supported by the Ministry of Education and Research for various cities.

## F4.5 Advantages

- AQUA-Selekt allows the forecasting of sewer condition of an entire network based on the CCTV data from a representative sample. This helps in the overall planning and evaluation of sewer rehabilitation and maintenance and helps to target problem areas.
- This method used is claimed to be efficient with clear cost benefits, particularly for large sewer systems of 1000 km and over.
- System sections that are in particular need of rehabilitation can be detected early and given priority for complete inspection and rehabilitation.
- PC based software that requires MS-Windows 95/98 and MS Access 2000 to be installed as minimum requirements (software cannot be used on other operating systems).

## F4.6 Limitations

- AQUA-Selekt was developed for the European context. Vendors only available in Germany. Requires CCTV data of selected sewer sections in order for the forecasting model to be effective.

**Table F-4. Summary AQUA-Selekt.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Sewer pipes. |
| | Granularity | System and asset level. |
| | Service area | Wastewater. |
| Technical suitability | Focus of analysis | Forecasting of sewer condition using representative CCTV-inspection data. |
| | Scalability of tool/approach | Better suited to medium to large authorities where CCTV data is available. |
| | Commercialization | Commercial software available from Germany. |
| | Previous/existing use of the tool | Used by several European authorities and has a handful of users in other areas. |
| | Ease of validation | Validation is possible only through site surveys. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Wastewater only; system level only. |
| | Integration with other tools/GIS | None. |
| Utility technical capacity | Asset management sophistication | Aimed at level of asset management where CCTV data is available. |
| | In-house skills required | Professional asset manager/engineer |
| | Technology required | PC based tool. Windows based operating system. Requires Microsoft Access 2000 |
| | Documentation | On-line help and detailed documentation provided. |
| | Data Requirements | CCTV data required and MS Access data files used. |
| | Linking to asset data | Exports and imports to/from Microsoft Access database. |
| | Availability of software and technical support | Technical support available. On-line forum. |
| | Usability | Simple operation of the Windows 32-Bit program using Explorer-style navigation structure. |

## F4.7 Bibliography


1. Eisenbeis, P., P. Le Gauffre, and S. Saegrov, *Water Infrastructure Management: An Overview of European Models and Databases*, AwwaRF Infrastructure Conference, Baltimore MD, 2000.
2. Herz, Raimund K., *Aging Processes And Rehabilitation Needs Of Drinking Water Distribution Networks*, Journal of Water, SRT-Aqua Volume 45, pp 221-231, 1996
3. AQUA-Selekt homepage, http://www.sewer-rehabilitation.com/, accessed 2006
4. DIN EN 752-5: 1997 Drain and sewer systems outside buildings - Part 5: Rehabilitation

# F5.0 AQUA-WertMin

## F5.1 Overview

AQUA-WertMin is a software package developed in Germany to assist infrastructure managers with the planning of CCTV-inspection, rehabilitation and new construction strategies for sewers networks.

AQUA-WertMin calculates the current market value of assets, forecasts the deterioration of pipe condition and assesses future rehabilitation needs using inbuilt models and CCTV inspection data. It enables users to compare the costs of different rehabilitation strategies based on an economic analysis of costs and time of repair.

## F5.2 Main Principles

AQUA-WertMin is a PC based software tool. The user enters pipe and manhole (assets) condition scores derived from CCTV inspections into the application. The software then assigns one of the following six classifications to each asset in the network, as described in the Table F-5.

**Table F-5. Asset Condition Classification System.**

| Classification | Description |
|---|---|
| Class 6 | Excellent condition – no observed defects. |
| Class 5 | Good condition – few defects observed, repair as needed. |
| Class 4 | Fair condition – minor defects observed that will require repairs in long-term plan. |
| Class 3 | Poor condition – defects observed that will require major repairs, but no rehabilitation in the mid-term plan. |
| Class 2 | Very poor condition – defects observed that require major rehabilitation, but not replacement in the near-term plan. |
| Class 1 | Pipe failed – needs immediate replacement. |

The software calculates the probability of an asset (or group of like assets) transitioning from one condition class to the next lower (worse) class. To determine the transitional function, the software applies a survival model for groups of similar sewer sections. The survival functions are calibrated using data collected from the network inspection records including year of pipe installation, year of inspection, pipe diameter, and pipe condition.

Modules are also provided for the calculation of asset values, and replacement/rehabilitation costs, which enables the user to compare the costs of different rehabilitation strategies based on an economic analysis.

## F5.3 Application

AQUA-WertMin is designed to assist with the planning of CCTV-inspection, rehabilitation and new construction strategies for sewer network assets. The program follows the guidelines for cost-minimizing maintenance of sewers by the Ministry of Environment and Transport of the German federal state Baden-Württemberg of December 2000.

## F5.4 Practical Considerations

- The software is readily available, commercialized, and used by several European authorities with a handful of users in other areas.
- The software uses a simple Windows Explorer-style navigation structure.

- All data can be selected using specific fields and exported to Microsoft Access 2000 or 97 databases.

## F5.5 Advantages

- Program installation is simple with step-by-step instructions.
- AQUA-WertMin has a consistent and easy-to-use user interface with Explorer-style navigation structure. On-line help is also available
- Freely-configurable import function for Access databases from version 2.0 and databases linked using ODBC.
- All data can be selected using specific fields and exported to Microsoft Access 2000 or 97 databases.

## F5.6 Limitations

- AQUA-WertMin was developed for the European context.
- Vendors are only available in Germany.

**Table F-6. Summary AQUA WertMin.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Sewer pipes. |
| | Granularity | System and asset level. |
| Technical suitability | Focus of analysis | Planning of CCTV-inspection, renovation and new construction strategies for wastewater networks. |
| | Scalability of tool/approach | Better suited to medium to large authorities where CCTV data is available. |
| | Commercialization | Commercial software available from Germany. |
| | Previous/existing use of the tool | Used by several European authorities and has a handful of users in other areas. |
| | Ease of validation | Validation is possible only through site surveys. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Wastewater only; asset to system level. |
| | Integration with other tools/GIS | None. |
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management where CCTV data is available. |
| | In-house skills required | Professional asset manager/engineer. |
| | Technology required | PC based tool. Windows based operating system. Requires Microsoft Access 2000. |
| | Documentation | On-line help and detailed documentation provided. |
| | Data Requirements | CCTV data required and Microsoft Access data files used. |
| | Linking to asset data | Exports and imports to/from Microsoft Access database. |
| | Availability of software and technical support | Technical support available. On-line forum. |
| | Usability | Simple operation of the Windows 32-Bit program using Explorer-style navigation structure. |

## F5.7 Bibliography

1. Herz, Raimund K., *Aging Processes And Rehabilitation Needs Of Drinking Water Distribution Networks*, Journal of Water, SRT-Aqua Volume 45, pp 221-231, 1996

2. Eisenbeis, P., P. Le Gauffre, and S. Saegrov, *Water Infrastructure Management: An Overview of European Models and Databases*, AwwaRF Infrastructure Conference, Baltimore MD, 2000.
3. AQUA-WertMin homepage, http://www.sewer-rehabilitation.com/, accessed 2006
4. Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A-S., and Erickson, M. *Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems*, EPA, EPA/600/R-02/029, 2002

# F6.0 AwwaRF's Manager Software

## F6.1 Overview

AwwaRF's Water Treatment Plant Infrastructure Assessment Manager (Manager Software) is a software based tool that allows the user to manage information relating to treatment plant assets. The software provides procedures and instructions to gather information on the condition and criticality of water treatment facilities and their components, and includes financial accounting capabilities from the unit level through the facility level.

## F6.2 Main Principles

There are three parts to the Manager Software: the toolbar, tree and data viewer. The tree allows the structure of the treatment plant facility to be input according to a consistent asset hierarchy. For example, from the facility level, the plant is conceptually broken down in terms of systems (e.g., raw water systems) and subsystems (e.g., raw water intake), units (such as screening), and finally individual components such as bar screens and control panels. The user can represent the treatment plant hierarchy using the options in the tree.

Once the tree has been set up, the user navigates throughout Manager Software by clicking on different systems, subsystems, and units, and can then record information against the assets detailed at that level in the hierarchy. The user can input the following data:

- Criticality (to show relative importance of the plant item).
- Condition assessment, a unit can have a condition grading/rating 0 (inoperable) through to 4 (excellent), with a capacity to record 'unknown'.
- Safety impact to human health if it should fail.
- Weighting and criticality; to give relative importance to an asset within the hierarchy.

Other information can be input such as, photos, assessment considerations, acquisition cost, replacement cost, and so forth.

A condition scoring system is used to summarize condition. This incorporates both a condition rating at the unit level and a weighting of the unit's importance to the plant's overall ability to produce water. The Manager Software tabulates the scoring at the subsystem, system, and facility levels and generates various reports.

## F6.3 Application

AwwaRF's Manager Software is designed to facilitate the management of condition and asset data for water treatment works.

## F6.4 Practical Considerations

- The product is an output of a research project and is freely available through AwwaRF.

## F6.5 Advantages

- The Manager Software provides procedures and instructions to gather information on the condition and criticality of water treatment facilities and their components.
- Through the tree structure, the software organizes the assessment process around the evaluation of systems rather than engineering/maintenance disciplines. A review of non-destructive assessment methods is also included within the Manager Software.

- The Manager Software allows for wide variations in the type and size of facilities and in the experience of the staff who will perform the assessment.
- It includes financial accounting capabilities from the unit level through the facility level.

## F6.6 Limitations

- Functionality would ideally be integrated into corporate systems, rather than a stand-alone tool.

**Table F-7. Summary AwwaRF's Manager.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Water treatment works. |
| | Granularity | System down to unit and component level. |
| | Service area | Potable. |
| Technical suitability | Focus of analysis | Representing asset and condition data within a consistent framework. |
| | Scalability of tool/approach | Useable by any utility, but better suited to utilities without equivalent functionality in corporate systems. |
| | Commercialization | Software available from AwwaRF. |
| | Previous/existing use of the tool | Practical use is unknown. |
| | Ease of validation | N/A |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | System level, water treatment plants only. |
| | Integration with other tools/GIS | None. |
| Utility technical capacity | Asset management sophistication | Aimed at level of asset management where corporate systems have not been developed. |
| | In-house skills required | Professional asset manager/engineer. |
| | Technology required | PC based tool. Windows based operating system. |
| | Documentation | Documented through AwwaRF report. |
| | Data Requirements | Asset hierarchy, cost and condition data. |
| | Linking to asset data | Asset hierarchy embedded in software. |
| | Availability of software and technical support | Supported in help files and through AwwaRF report. |
| | Usability | Simple operation of the Windows 32-Bit program using Explorer-style navigation structure. |

## F6.7 Bibliography

1. AwwaRF. Water Treatment Plant Infrastructure Asset Management: Users Manual, prepared by L. Elliot et al, AWWA Research Foundation and American Water Works Association, USA, 2001

# F7.0 Barcol Hardness Test

## F7.1 Overview

The Barcol hardness test is a quick and simple non-destructive test using a Barcol Impressor, which gives a relative measure of the hardness of rigid materials. It is can be used, for example, on plastic and cementitious pipes.

Barcol hardness can be converted to other hardness measures such as Vickers hardness but does not relate to any other physical quantity (Dorn et al., 1996).

## F7.2 Main Principles

The Barcol Impressor is either manually operated by pressing the device into the sample a set distance and reading hardness off a graduated dial between 0 and 100, or is electronically controlled. Electronically controlled devices can be hand held or mounted depending on the samples to be tested. Harder materials give a higher reading, with materials that are either too hard or too soft not registering.

The Barcol hardness test provides a relative measure of material hardness. Barcol hardness is most useful for cementitious pipes, as changes in hardness can indicate areas of deterioration, but the technique can also be used on materials such as plastic, aluminum and brass.

## F7.3 Application

The Barcol hardness test can be used to measure the surface hardness of any asset dependant on material. Asset that can be inspected include pipes and coatings, testing can be conducted in the lab or in the field.

- The Barcol Impressor is referred to in a number of standards ASTM D2583-95, ASTM B 648-78, ASTM E140-97.

## F7.4 Practical considerations

- The Barcol Impressor is widely available from numerous commercial suppliers. The Barcol Impressor is simple to use, hand held and readily portable, weighing less than 1 kg.
- Manual testers require no power and the reading is taken from dial on tester. Hand held digital versions are also available.
- Variance in the results depends on the material being tested; homogenous materials have a lower variance than heterogeneous materials. A large number of tests should be undertaken to provide statistically meaningful averages, especially for heterogeneous materials.
- The tester should be used on flat surfaces; the legs of the tester do not have to be on the sample but should be supported so that the indenter is perpendicular to the surface being tested. Multiple tests should be conducted on all materials, with heterogeneous materials needing significantly more readings than homogenous materials. Different models of the Barcol Impressor are available that give higher accuracy depending on the hardness of the material being tested (ASTM D2583).
- Resources required depend on the assets being inspected. Buried assets need to be exposed and have any coatings removed, man entry such as into manholes may require multiple personnel, dependant on safety requirements.

- The Barcol hardness test has been used to assess deterioration of AC and cementitious pipes.

## F7.5 Advantages

- The Barcol Impressor is quick and easy to use and has repeatable measurements on homogeneous materials. The test can be used on both cementituous and polymeric materials (Dorn et al., 1996).

## F7.6 Limitations

- Due to the small area tested each time, the Barcol Impressor is used the results can show a high degree of scatter in heterogeneous materials, requiring large numbers of measurements to be taken.
- Hardness measurement is an arbitrary scale and does not relate to any other physical property such as strength (Dorn et al., 1996)

**Table F-8. Summary Barcol Hardness.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Tester can be used on assets made from the materials listed below. |
| | Material type | Rigid Plastics, uPVC, ABS, mPVC, oPVC and GRP and cementituous materials. |
| | Service Area | Potable and wastewater. |
| | Access requirements | Portable hand held device, but requires access to the asset surface. |
| | Limitations relating to asset condition | Any coating applied to the surface of the asset should be removed prior to testing. |
| | Limitations relating to asset size/geometry | Test should be preformed on a flat surface, excessive curvature is an issue. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | For man entry standard safety procedures should be followed, otherwise the asset can remain on-line. |
| Technical suitability | Assessment parameters | This technique measures the Barcol hardness, Barcol hardness can be converted to other measurements of hardness such as Vickers Hardness. |
| | Integration with software tools | Stand alone; no integration with computerize tools/equipment. |
| | Commercialization of tool | Barcol Hardness testers are available off the shelf. |
| | Previous/existing use of the tool in sector | Some use in assessing deterioration of cementitious materials. |
| | Accuracy/reliability | Semi quantitative (relative) measure. Good repeatability for homogeneous materials. High variance for heterogeneous materials. |
| | Ease of validation of results | Indicative results only. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy to use by following simple procedure. |
| | Technology required (level of tool sophistication) | Stand alone tool. |
| | Documentation | ASTM D2583-95, ASTM B 648-78, ASTM E140-97. |

| | Criteria | Assessment |
|---|---|---|
| | Availability of technical support | Technical support available from retailers and from Internet. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | Resources required depend on assets being inspected. Buried assets need to be exposed and have any coatings removed, man entry such as into manholes may require multiple personnel dependant on safety requirements. |

## F7.7 Bibliography


1. ASTM D2583 95, Standard test method for indentation hardness of rigid plastics by means of a Barcol Impressor.

2. ASTM E140-97 Standard Hardness Conversion Tables for Metals E1842-96 Standard Test Method for Macro-Rockwell Hardness Testing of Metallic Materials

3. ASTM B648-78 Standard Hardness Conversion Tables for Metals E1842-96 Standard Test Method for Macro-Rockwell Hardness Testing of Metallic Materials

4. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996.

5. Randall-Smith, M., Russell, A. and Oliphant, R., *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992

# F8.0 Broadband Electromagnetic

## F8.1 Overview

The broadband electro magnetic (BBEM) technique is an eddy current method. In eddy current methods, the thickness of a pipe wall is measured by inducing magnetic fields in the material. While conventional eddy current inspection techniques use a single frequency (or a narrow frequency bandwidth), BBEM induction techniques record data over a broad range of frequencies. Since the depth of penetration is dependent on the frequency of excitation, this allows information from a range of depths to be obtained.

The BBEM technique works by passing an alternating current through a transmitter coil at the surface of the pipe, which generates an alternating magnetic field. Flux lines from this magnetic field pass through the metallic pipe wall, generating a voltage across it. This voltage produces eddy currents in the pipe wall that produce their own, secondary magnetic field. By measuring the strength of this magnetic field or the eddy current that produces it, the remaining metallic wall thickness can be detected.

The technique is non-destructive and commercial suppliers of BBEM state that signal can be received through all forms of external coating, and in all ferrous materials.

## F8.2 Main Principles

Eddy current methods measure the wall thickness of a pipe by sensing the attenuation and phase delay of an electromagnetic signal that has passed through the pipe wall. Defects on the pipe are detected because they change the distribution of the eddy currents in the objects being examined. For example, if the pipe wall is cracked, the currents are forced to go round or under the crack, causing the magnetic field produced by the eddy currents and the voltage in the pick-up coil to change. Eddy current inspection techniques are most sensitive to cracks and other abrupt changes in the metal, and are least sensitive to gradual changes to wall thickness on the far side of the pipe wall from the coils. For these reasons, and the low frequencies necessary to overcome the 'skin effect', the classical eddy current technique is not applied to water pipelines.

While conventional eddy current inspection techniques use a single frequency (or a narrow frequency bandwidth), BBEM induction techniques record data over a broad range of frequencies and consequently have advantages over conventional techniques. The principle of BBEM is to transmit a signal that covers a broad frequency spectrum (i.e., perhaps three decades). The received signal resulting from a broadband transmission contains more information, and allows detection and quantification of various wall thicknesses, as well as the effective conductivity of the complex through-wall components of the pipe.

Tools based on BBEM techniques measure the full-wave secondary magnetic field resulting from a transient input signal. By recording the full waveform response, it is possible to obtain information on both the magnetic and the electrical properties of ferrous pipes. The transient input signal generates multiple frequencies, typically 50 Hz to 50kHz. The wide acquisition bandwidth negates the requirement for tuning or setting fixed frequencies depending upon pipe wall thickness and composition.

Instruments for acquiring BBEM data are based on the time-domain electromagnetic technique (TDEM), where the transient decay of the magnetic field is measured following the interruption of current flow in the transmitter coil. The BBEM variant has been specifically designed for the study and assessment of water supply systems.

The technique can be used either internally or externally. Internal inspection requires full-bore access. When used externally, the pipe is exposed at the site of investigation and the BBEM tool scans the pipe outer surface. Results are reported graphically or as color contour plots, as in shown Figure F-2.

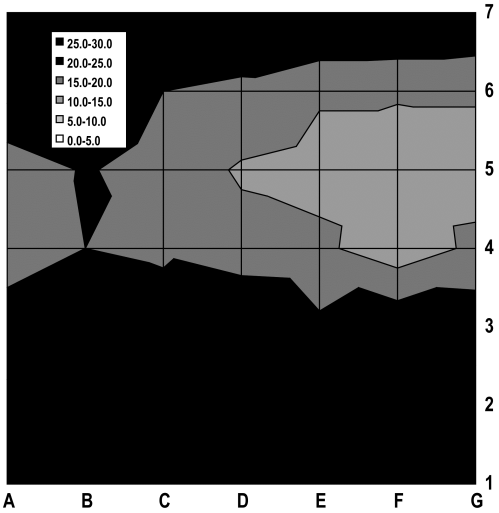


**Figure F-2. Color Contour Plot Representing Variations in Pipe Wall Thicknesses.**

## F8.3 Application

- Broadband electromagnetic techniques can be used to assess ferrous pipe wall condition and locate illegal tap-ins.
- Tools are available for both external and internal use.

## F8.4 Practical considerations

- BBEM inspection tools and services are commercially available.
- Practical use of this technique is reported in the literature and trade journals.
- The tool gives quantifiable results in the form of contour plots.
- The condition assessment (internal) probe can be winched or rodded through de-pressurized pipes.

## F8.5 Advantages

- Non-destructive condition monitoring techniques based on electromagnetic induction principles can provide useful information to assist with pipeline replacement and rehabilitation decisions for critical mains.
- Pipe wall condition assessment is by means of an internal condition assessment probe; this allows continuous data to be recorded along extensive lengths of pipeline.
- The technique is able to survey through external coating and internal linings.
- There is no upper limit on pipe diameter.

## F8.6 Limitations

- Use of the tool requires pipe to be depressurized during the assessment and full bore access for internal inspections.
- Internal inspection rate is reportedly only a few feet per day in large diameters.

**Table F-9. Summary Broadband Electromagnetic.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Water pipes. |
| | Material type | Steel, cast iron, ductile iron. |
| | Service Area | Potable. |
| | Access requirements | Internal: full bore access required; external: exposure of pipe surface. |
| | Limitations relating to asset condition | No limitations relating to asset condition provided direct contact with the pipe wall is available. |
| | Limitations relating to asset size/geometry | Minimum 3". |
| | Continuous/discrete | Continuous. |
| | Destructive/non destructive | Nondestructive. |
| | Interruption to supply/function | Pipe must be depressurized. |
| Technical suitability | Assessment parameters | Remaining wall thickness. |
| | Integration with software tools | Fully integrated software for analysis of data. |
| | Commercialization of tool | Commercially available. |
| | Previous/existing use of the tool in sector | Commercial use of the tools reported in literature and trade journals. |
| | Accuracy/reliability | Quantitative assessment; but varied sensitivity to defects. |
| | Ease of validation of results | Validation by other measurement is required, though data collected can be recalibrated at any time after the inspection. |
| Utility technical capacity | Asset management sophistication required | Associated with high levels of asset management sophistication. |
| | Skills required (level of tool sophistication); usability | Tool operation typically by a third party. |
| | Technology required (level of tool sophistication) | Specialized equipment and dedicated computer software. |
| | Documentation | Use and development documented in the literature. |
| | Availability of technical support | Tool operation typically by a third party. |
| Economic factors | Cost per inspection | High cost associated with access and tool use. |
| | Resource requirements | Sufficient manpower to undertake enabling work and inspection. |

## F8.7 Bibliography


1. Burn, L.S., Eiswirth, M., DeSilva D. and Davis P., Condition Monitoring and its Role in Asset Planning, Pipes Wagga Wagga 2001, Charles Sturt University, Wagga Wagga, N.S.W., 2001

2. Lillie, K., Reed, C. and Rodgers, M. A. R., 2004, *Workshop on Condition Assessment Inspection Devices for Water Transmission Mains*, AwwaRF, USA, 2004

# F9.0 Carbonation Testing and Petrographic Examination

## F9.1 Overview

In normal high quality reinforced concrete, the steel reinforcement is chemically protected from corrosion by the alkaline nature of the concrete. This alkalinity causes the formation of a passive oxide layer around the steel reinforcement. However, over time the concrete reacts with atmospheric carbon dioxide and sulfur dioxide to cause gradual neutralization of the alkalinity from the outside surface inwards. This process is known as carbonation and over time the concrete around the steel reinforcement is neutralized allowing it to corrode, leading to the deterioration of the concrete through cracking and spalling. Carbonation testing measures the depth of carbonation and can be determined using onsite or laboratory based assessment techniques. Core samples are taken, but the technique is in essence non-destructive.

## F9.2 Main Principles

The depth of carbonation can be measured on a freshly exposed core section of concrete by spraying with a phenolphthalein indicator spray solution. The indicator spray will turn pink in color when the concrete is alkaline ($pH \geq 9.2$). If the indicator spray remains colorless then the concrete is found to be carbonated. The depth of carbonation exists in a more or less even zone extending to a critical depth from the surface.

The rate at which carbonation occurs is a function of concrete quality, in particular the water/cement ratio and compaction achieved during construction. It is generally accepted that the rate in which carbonation occurs is inversely proportional to the square root of the age of the structure. However, recent research suggests that the square root relationship is only applicable for concretes which have been exposed to nominal humidity's of 50%. As humidity increases, the power function is found to decrease. As a result of this relationship, the carbonation depth is found to be lower for concretes that have been continuously exposed to higher humidity.

Assessments conducted in the laboratory such as petrographic examination, allow a much more detailed assessment to be conducted on the concrete quality than can be undertaken by other methods. Petrographic examination typically involves cutting a 20 mm thick slice (plate) from a concrete core with the plate then polished to give a high quality surface that can be examined with a microscope. The following characteristic properties of the sample are then determined:

- The size, shape and distribution of coarse and fine aggregate.
- The coherence, color, and porosity of the cement paste.
- The distribution, size, shape, and content of voids.
- The composition of the concrete in terms of the volume proportions of coarse aggregate, fine aggregate, paste and void.
- The distribution of fine cracks and micro-cracks. Often the surface is stained with a penetrative dye, so that these cracks can be seen. Micro-crack frequency is measured along lines of traverse across the surface.

## F9.3 Application

Carbonation testing is commonly undertaken on structures constructed from concrete materials, to determine the existence and level of carbonation.

- BS 8110 Structural use of concrete. Code of practice for design and construction

## F9.4 Practical Considerations

- Onsite analysis using phenolphthalein is a quick and simple method to obtain an indication of carbonation without the need to obtain core samples.
- More complex assessment techniques conducted in the laboratory require skilled laboratory staff to prepare samples from cores for analysis and interpretation of experimental results.
- While the phenolphthalein test is a good indication the presence of free lime, it only indicates a pH above 9, and passivation requires a pH $\geq$ 11.

## F9.5 Advantages

- Analysis techniques conducted onsite using phenolphthalein can, in some applications, be undertaken without the need to take core samples.

## F9.6 Limitations

- A phenolphthalein test may return a positive result even if alkalinity has reduced to a pH < 11, where passivation has been lost.
- Materials that contain carbonation along micro-cracks and diffusion paths in poorly compacted concrete may not be readily revealed by the phenolphthalein analysis methods.
- Laboratory based assessment techniques require skilled technical staff who have been trained and have relevant experience in the preparation, analysis and interpretation of experimental results.

**Table F-10. Summary Carbonation Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Concrete assets in contact with air or soil. Can also be used on dispersive soils and crushed stone base materials. |
| | Material type | Cementituous. |
| | Service area | Potable and wastewater. |
| | Access requirements | Direct contact with concrete surface. Surface coatings should be removed. |
| | Limitations relating to asset condition | No restriction. |
| | Limitations relating to asset size/geometry | No limitations relating to size. |
| | Continuous/discrete | Discrete readings. |
| | Destructive/non destructive | A core is required to be removed. |
| | Interruption to supply/function | The asset can remain in use and does not need to be taken off-line. |
| Technical suitability | Assessment parameters | Depth of carbonation in mm. |
| | Integration with software tools | Stand alone tool. |
| | Commercialization of tool | Test methods are fully developed and are available from a wide range of commercial vendors. |
| | Previous/existing use of the tool in sector | Widespread use throughout many sectors. |
| | Accuracy/reliability | Qualitative or quantitative measurement of depth of carbonation can be obtained. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy to use by following simple procedure. Basic training is recommended. |
| | Technology required (level of tool sophistication) | Low level of technological sophistication is needed for hand held, manual tools. |
| | Documentation | AASHTO T-259 and AASHTO T-260.<br>BS 8110. |
| | Availability of technical support | Technical support widely available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. |

## F9.7 Bibliography


1. BS 8110 Structural use of concrete. Code of practice for design and construction
2. Chemical Analysis' article on MG Associates Construction Consultancy Ltd website. http://www.mg-assoc.co.uk/serv04.htm Accessed 2006

# F10.0 CARE-S

## F10.1 Overview

CARE-S (Computer Aided Rehabilitation of Sewer and Storm Water Networks) is a computer-based system for sewer and stormwater network management developed under a collaborative research project supported by the European Commission under the 5th Framework program, intended to contribute to the implementation of the key action "sustainable management and quality of water."

CARE-S aims to allow cost-efficient programs of maintenance, repair and rehabilitation of sewer networks to be developed. In structure, CARE-S is a suite of PC based software tools developed separately, and linked within a common framework by a decision support system (DSS).

The overall rehabilitation planning process is derived from the European Standard; BS EN 752-5:1998 "Drain and sewer systems outside buildings. Rehabilitation." This planning process is done within the context of an integrated catchment management approach.

## F10.2 Main Principles

A CARE-S project is used as the basis of the analysis. A project is a collection of data items, analyzes and results pertaining to an area or areas of interest, which may be geographic (e.g., a city network) or thematic (flooding or environmental issues).

CARE-S has a central rehabilitation manager module and variations in data holdings are handled by import/export protocols. Specific CARE-S tools are included that provide the following functions:

1. Performance indicator management.
2. Structural condition (CCTV data classification models, sewer assessment models, deterioration process models).
3. Hydraulic performance.
4. Rehabilitation technology information system (operational and structural rehabilitation options).
5. Socio-economic consequences (impact of rehabilitation on socio-economic costs, rehab impact on social life quality, public acceptance).
6. Multi-criteria decision support (choice of rehabilitation technology, selection of priority projects, exploration of rehab programs and technologies).

The CARE-S approach can be used at a range of granularities. CARE-S is not intended to bind together the external tools in a fixed and constraining way, but rather to allow the user to use them individually or in a sequence appropriate to the data available for the analysis.

## F10.3 Application

CARE-S is a flexible computer-based system for improving sewer and stormwater network management. The overall rehabilitation planning process is derived

- BS EN 752-5:1998 "Drain and sewer systems outside buildings. Rehabilitation"

## F10.4 Practical considerations

- The tools are PC based and run under the Windows operating system. While not commercialized as yet, the CARE-S exists in prototype form. The use by third parties should therefore be supported by some of the developers for the time being.
- Several projects based on the CARE-S methodology are emerging in Europe and Australia. These projects will serve to verify the suitability of CARE-S modules to support management of wastewater networks, and are expected to show the pathway towards full commercialization.
- For full details on the CARE-S project and prototype tool see, http://care-s.unife.it/ and/or Saegrov (2006) (see Bibliography).

## F10.5 Advantages

- CARE-S has allowed the integration of tools for managing sewerage and stormwater networks. The results can be presented by reports, in tables and graphically (GIS).
- A significant effort has been made to allow companies to maintain their own data formats, yet import them into CARE-S in the standard form required by the suit of tools.

## F10.6 Limitations

- The software is still a prototype and thus in need of further development.
- The adoption by water authorities is in an early stage and the practical results from using CARE-S have not yet obtained.
- Although the methodologies of CARE-S are generic and independent of worldwide practice, there are some designs that are made in light of European practices (e.g., classification of CCTV inspection).
- Approaches in the United States may differ from those adopted by the European partners, which could affect relevance to the United States market.

**Table F-11. Summary CARE-S.**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Wastewater networks. |
| | Granularity | Spatially drainage area and below; thematic analysis is also supported. |
| | Service area | Wastewater. |
| Technical suitability | Focus of analysis | Service levels, budget setting, environmental impact, life cycle cost, rehabilitation planning. |
| | Scalability of tool/approach | Procedure and individual tools can be used by any size company. However it should be noted that the complete integrated package is data-intensive and has the associated cost issues. |
| | Commercialization | Not commercialized. |
| | Previous/existing use of the tool | Used during case studies for development of tool and for succeeding projects. |
| | Ease of validation | Validity depends on models and data; independent validation difficult. |
| | Flexibility with respect to analysis (asset types) and granularity (system, asset level) | Wastewater only; asset to system level. |
| | Integration with other tools/GIS | Not integrated; but data interface (import/export) provided. |
| Utility technical capacity | Asset management sophistication | Generic approach; intended to map onto company specific systems. CARE-S provides a suite of tools that compliment existing asset management approaches. |
| | In-house skills required | Professional engineering skills required. |
| | Technology required | PC based. |
| | Documentation | A range of papers written on approach; help files included in package. |
| | Data Requirements | Flexible, some tools can be used with limited data, while other tools are data hungry. |
| | Linking to asset data | Data import facilities are provided. |
| | Availability of software and technical support | Software is not in a fully commercial format; technical support is available from an international networks of developers on a consultancy basis. |
| | Usability | Installation and help tools provided Support from developers required. |

## F10.7 Bibliography


1. De Silva, D., Burn, S., Davis, P. and Moglia, M. *Development of a Decision Support System for Sewer Rehabilitation*, Pipes Wagga Wagga 2003, Wagga Wagga, NSW, Australia, 21–23 October 2003
2. BS EN 752-5:1998 "Drain and sewer systems outside buildings. Rehabilitation"
3. CARE-S homepage, http://care-s.unife.it/, accessed 2006
4. Saegrov, S. *CARE-S – Computer Aided Rehabilitation of Sewer and Storm Water Networks*, IWA Publishing, London. 2006

# F11.0 CARE-W

## F11.1 Overview

CARE-W is a computer-based system for water network rehabilitation planning developed under a collaborative research project supported by the European Commission under the 5th Framework program. CARE-W is a suite of PC based software tools operated via a decision support system (DSS).

## F11.2 Main Principles

CARE-W is intended to enable a utility manager to manage water distribution assets in a cost-effective manner and help to rehabilitate the right pipe at the right time, to avoid premature rehabilitation (i.e. rehabilitation of the wrong pipe), minimize interruption of water supply (i.e. due to unexpected pipe break), and resolve issues of poor water quality. Specific CARE-W tools include:

1. A scenario writer for developing consistent scenarios.
2. A performance indicator tool to measure the performance of the network with a range of key indicators.
3. A set of statistical tools to obtain probabilistic forecasts of pipe failures (bursts and leaks).
4. An annual rehabilitation planning system that uses a multi-criterion selection and ranking system that combines results from other CARE-W tools with additional information supplied by the user. It provides recommendations for pipes or groups of pipes that should be considered for rehabilitation in the short term.
5. A combined hydraulic/reliability model to analyze the loss of water supply due to bursts and leaks.
6. A long-term planning module, which analyzes the necessary investment level in the coming decades and how this is influenced by different rehabilitation strategies.

The CARE-W suite of tools is designed to be used together, though individual tools can be used in isolation.

## F11.3 Application

CARE-W is a PC based suite of tools to enable the effective use of water pipes, including when to rehabilitate a pipe.

## F11.4 Practical considerations

- The tools are PC based and run under the Windows operating system. By the end of the research project the tools were provided in a prototype form.
- The use by third party should, until commercialization, be supported by at least one of the developers.
- Several projects based on the CARE-W methodology are emerging in Europe. These projects also serve to verify of the suitability of CARE-W modules to support management of drinking water networks, and are expected to show the pathway towards full commercialization.

## F11.5 Advantages

- An attempt has been made to provide an integrated tool for managing water supply networks. The results are presented by reports, in tables and in graphical/GIS format.
- The methodologies of CARE-W are generic and not limited to European practices worldwide, allowing implementation independent of location.

## F11.6 Limitations

- As noted above, the software is still in development and is not fully commercialized. Adoption by water authorities is in an early stage.

**Table F-12. Summary CARE-W.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Water networks. |
| | Granularity | Networks, pipe cohorts and pipe level. |
| | Service area | Potable. |
| Technical suitability | Focus of analysis | Service levels, budget setting, environmental impact, life cycle cost, rehabilitation planning. |
| | Scalability of tool/approach | Scaleable; procedure and individual tools can be used for any size company. The integrated package is data-intensive and the cost of its use is likely to be justified only by companies representing more than 50.000 customers. |
| | Commercialization | Not commercialized. |
| | Previous/existing use of the tool | Used during case studies for development of tool. Some European cities have started using the tools for their water network management, in the first stage to define management information needed. |
| | Ease of validation | Validity depends on models and data; independent validation difficult. |
| | Flexibility with respect to analysis (asset types) and granularity (system, asset level) | Potable only; asset to system level. |
| | Integration with other tools/GIS | Not integrated; though data interface (import/export) provided. |
| Utility technical Capacity | Asset management sophistication | Generic approach; intended to map onto company specific systems. CARE-W provides a suite of tools that compliment existing asset management approaches. |
| | In-house skills required | Professional engineering skills required. |
| | Technology required | PC based. |
| | Documentation | A range of papers written on approach; help files included in package. |
| | Data Requirements | Flexible, some tools can be used with small amounts of data while others are data demanding. |
| | Linking to asset data | Data import facilities are provided. |
| | Availability of software and technical support | Software is not in a fully commercial format; technical support is available from an international network of developers on a consultancy basis. |
| | Usability | Installation and help tools provided. Support from developers required. |

## F11.7 Bibliography

CARE-W Homepage, http://care-w.unife.it/intro.html, accessed 2006

Undated papers from the CARE-W project CD reviewed include:

- S Sægrov, What is CARE-W?
- Algaard, E. and P. Campbell, Critical Needs for Rehabilitation Planning
- P Conroy, P. Using CARE-W to manage water distribution pipes
- H. Alegre; L. Tuhovcak & P. Vrbkova, Performance Management and Historical Analysis: The Use of the CARE-W PI Tool by the Brno Waterworks Municipality
- P. Eisenbeis; M. Poulton; K. Laffréchine,Technical Indicators for Rehabilitation: failure forecast and hydraulic reliability tools
- Le Gauffre, P & Laffréchine, K; Schiatti, M; Baur, R., Identifying priority projects for annual rehabilitation planning
- Hulance, J., The CARE-W Rehabilitation Scheme Developer

# F12.0 CCTV Inspection

## F12.1 Overview

CCTV inspection is the standard technology for the non-destructive assessment of the internal condition of sewers and stormwater pipes and has been employed for over 20 years. CCTV inspection is conducted by introducing a CCTV module into the pipe being inspected. As the pipe is inspected, the operator records features of interest, which are used for condition assessment of the pipe. This enables maintenance budgets to be allocated and provides value by identifying problems before they become engineering and financial issues.

CCTV inspection can also be conducted on water pipes, but this use is less common. However, CCTV is commonly used as part of water main rehabilitation processes such as in situ lining.

## F12.2 Main Principles

A typical CCTV module comprises of a color CCTV camera and lighting system mounted on a wheeled carriage. Small modules are moved through the sewer by a winch and pulley system. Larger pipes allow self propelled modules to be used, some with on-board power. The larger modules all use an umbilical cord system. The umbilical cord systems supply power, allows for communication to the control center and acts as a retrieval device should the module become wedged in the pipe or lose power. The images captured by the CCTV camera are sent to the control center to allow remote control of the module and for image storage. Images are sent along coaxial or twisted pair cable in most units, with more advanced units using optical fiber.

In most modules the CCTV camera can be panned and tilted for close up observation of defects. The image captured from the CCTV camera is stored straight to hard drive (some systems use DVD, or VHS tape in older systems). More advanced units such as the Panaramo™ and Sewer Scanner and Evaluation Technology (SSET) systems have fish-eye optics for 360° view of the pipe, coupled with digital image manipulation for an unfolded view of the whole pipe circumference. The fish-eye lens allows a view of the whole pipe circumference without needing to pan or tilt the camera. Condition assessment of connections can also be made using axial/lateral inspection cameras which deploy from specially designed modules.

Condition assessment is made by professionals, either during inspection or at a later time using the recording. For wastewater pipelines, standards are available for qualitative and quantitative grading of defects and a system for ‘condition grading’ commonly used on which rehabilitation decisions can be based. A condition grade is allocated that represent the range of conditions from “like new” to “collapsed” or “collapse imminent.” The accuracy of a condition grading depends on an inspector’s experience.

CCTV inspection provides only an assessment of the internal surface, based on which further inspection utilizing tools that provide specific information on the pipe wall could be initiated.

Advances in digital imaging and computer software mean that progress is being made in the development of automated defect recognition and defect size quantification systems. In the future, when coupled with laser projection systems that provide quantitative data about the pipe ovality and cross sectional area, this technology may eliminate the need for human intervention in visual interpretation of the CCTV images.

## F12.3 Application

CCTV inspection is used to view and record visual images of the internal pipe surface. Generally CCTV inspection is used in gravity flow wastewater and stormwater pipes to establish the condition of the asset.

CCTV is also used in water pipes to assess the condition of internal cement mortar linings, evidence of internal corrosion in these lined pipes (corrosion shows up as staining on the cement mortar), build up of corrosion products and other obstructions.

## F12.4 Practical considerations

- CCTV inspection is widely used by water authorities to inspect wastewater and stormwater pipelines on a regular basis, for trouble shooting as well as for prioritizing renewal and rehabilitation expenditure. CCTV services are provided by numerous specialist contractors.
- Tool access in gravity flow wastewater and stormwater systems is through maintenance structures. Tool access in pressure pipelines requires cut-ins at regular intervals (100 m to 500 m, depending on cable length and pipe alignment).
- In some pipes, flow can potentially submerge the camera, for this reason inspection should be performed during low flow times between midnight and 5 AM. Alternately, sewers can be temporarily plugged to reduce the flow.
- For optimum results, pipes should be flushed and cleaned prior to inspection to remove surface encrustations and bio film layers, and expose the structure of the inner surface.
- The visual image needs to be analyzed manually by an experienced operator, although defect recognition software is being developed. The operators should be trained in order to ensure consistency and uniformity of the inspection results. Accurate data on pipe ovality is required.

## F12.5 Advantages

- Defects present above the flow surface can be located, identified and ranked by a trained operator.
- Technology is proven and widely available. Long lengths of mains can be inspected relatively quickly (greater than 1 km/day, depending on site conditions, state of pipe and flow conditions).
- Greater coverage per day is possible with large diameter pipes when remotely operated vehicles are used.
- Systems which incorporate fish-eye technology record a full view of a pipe during a single pass and allow full inspection to be done off-line using the recording. This reduces the time spent in each pipe system.

## F12.6 Limitations

- CCTV inspection provides only an assessment of the internal surface. The results are qualitative and require manual interpretation for analysis. The accuracy of a condition grading depends on an inspector's experience.
- Storage of records on VHS tape is cumbersome (this is overcome by digital recording and storage on hard drive or DVD).

**Table F-13. Summary CCTV Visual Inspection.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes; stormwater and wastewater pipeline infrastructure, water mains, although less so. |
| | Material type | Any pipe material. |
| | Service area | Predominantly wastewater, but also potable. |
| | Access requirements | Tool available for internal use only. Defects visually observable. Access to tool and umbilical cord has to be provided through manholes (wastewater) or through cut-ins at regular intervals depending on cord feed length and bends and obstructions on pipeline. |
| | Limitations relating to asset condition | No limitations relating to asset condition provided obstructions do not impede forward movement of camera. |
| | Limitations relating to asset size/geometry | Generally limited to pipes 90 mm and greater. However axial cameras can traverse pipes down to 25mm. |
| | Continuous/discrete | Continuous recording of CCTV image on VHS tape (analogue) or computer memory (digital). |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Low flow conditions are required for gravity pipes. Pressure pipes need to be off-line. |
| Technical suitability | Assessment parameters | Visual image of pipe internal surface analyzed manually. This can be used to allocate a condition state for the pipe. |
| | Integration with software tools | Software available for converting defect codes into grades. |
| | Commercialization of tool | Commercialized, widely available. |
| | Previous/existing use of the tool in sector | CCTV inspection routinely used by water authorities. |
| | Accuracy/reliability | Qualitative. |
| | Ease of validation of results | Validation possible only by comparison with other inspection techniques. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Interpretation of results for consistent data requires training. Professional skills required to utilize the information provided. |
| | Technology required (level of tool sophistication) | CCTV camera and related accessories, together with recording equipment. |
| | Documentation | Technique widely documented – generally only for waste and stormwater though sewer inspection codes. |
| | Availability of technical support | Tech support for tool is widely available. Support on analysis of results can be obtained from specialized consulting organizations. |
| Economic factors | Cost per inspection | Varies depending on pipe size, accessibility and purpose of survey. Can be priced on an hourly rate, a meter rate, or a per observation rate. |
| | Resource requirements | Requires team to operate camera and provide entry into pipeline. Extent of manpower required depends on pipe type and flow levels. |

## F12.7 Bibliography

Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996

Randall-Smith, M., Russell, A. and Oliphant, R, *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992

Ratliff, A., *An overview of current and developing technologies for pipe condition assessment*, Pipelines 2003, Pipelines 2003, ASCE 2004.

## F13.0 Concrete Electrical Resistance (Resistivity)

### F13.1 Overview of Tool

Resistivity meters are used for measuring the electrical potential fields to evaluate the corrosion rate of the reinforcing bars in the concrete. The influence of various concrete components on the electrical resistance can be investigated.

The electrical resistance of the concrete is measured according to the Wenner four-point method. Resistivity measurements can be performed for measuring the permeability of seal coats on concrete.

### F13.2 Main Principals

The corrosion of steel in concrete is an electrochemical process which generates a flow of current and can dissolve metals. The lower the electrical resistance, the more readily the corrosion current flows through the concrete and the greater is the probability of corrosion. Measurements of resistivity of concrete can provide an indication of the presence, and possible amount, of moisture in a concrete structure and therefore evaluate the extent and rate of corrosion of reinforcement indirectly.

Equipment consists of a resistivity probe with integrated electronics for resistivity measurement by the four-point method, a control plate for resistance probe and a display unit.

### F13.3 Applications

Resistivity meters can be used to investigate the influence of various concrete components on the electrical resistance of reinforcement. Resistivity meters are used in conjunction with corrosion analyzing instrument to evaluate the corrosion rate of the reinforcing bars in the concrete.

- There are no specific standards for concrete electrical resistance; however ASTM D-257, ANSI/ESD STM11.11, and ANSI/ESD STM11.2 cover resistivity meters which are specifically suited to the manufacturing industry and are used for making surface and volume resistivity measurements.

### F13.4 Practical Considerations

- Before taking resistivity measurements the reinforcement grid is marked out and electrical resistance measurements are taken between the bars to minimize the effect of the reinforcement.
- The results should be taken in the concrete's natural state i.e. natural moisture content. This value can be used to adjust the permeability measurements made using permeability testing techniques. After completing permeability testing an additional resistivity test can give the saturated (worst case) resistivity of the concrete.

### F13.5 Advantages

- Resistivity meters provide immediate on-site measurement of concrete resistivity.

### F13.6 Limitations

- Resistivity measurements are sensitive to the type of reinforcement, so assessment of the condition of a structure and the likelihood of corrosion needs to be made with careful reference to its construction.

- Testing often requires that at least two holes in the order of 6.5mm to a depth of approximately 10mm are drilled in order to insert probes.

**Table F-14. Summary Concrete Electrical Resistance (Resistivity).**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Reinforced concrete structures such as tanks, pipes, walls, dams, buildings, channels, weirs. |
| | Material type | Reinforced concrete. |
| | Service area | Potable and wastewater. |
| | Access requirements | Direct contact with surface of asset. If asset is buried, it must be exposed. |
| | Limitations relating to asset condition | Concrete surface must be fairly level. |
| | Limitations relating to asset size/geometry | No limitations relating to size of concrete element. Surface must be flat. |
| | Continuous/discrete | Continuous reading. |
| | Destructive/non destructive | Almost entirely non destructive, small drill holes may be required for certain tests. |
| | Interruption to supply/function | The asset can remain in use and does not need to be taken off-line unless internal (water side) surfaces need to be assessed. |
| Suitability | Assessment parameters | Corrosion rate of reinforcement bars in concrete. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Equipment is fully developed, available from selected commercial vendors. |
| | Previous/existing use of the tool in sector | Widespread use internationally on bridges and road infrastructure. Limited application in the water industry. |
| | Accuracy/reliability | Quantitative measurement. |
| | Ease of validation of results | Results are indicative and can be validated by using two other testing techniques: rebar linear polarization resistance and rebar electrical potential. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Relatively easy to use by following simple procedure. Trained staff can take measurements. |
| | Technology required (level of tool sophistication) | Low level of sophistication. |
| | Documentation | No specific standards, although tool is well documented by distributors. ASTM D-257, ANSI/ESD STM11.11, and ANSI/ESD STM11.2 cover resistivity meters which are specifically suited to the manufacturing industry and are used for making surface and volume resistivity measurements. |
| | Availability of technical support | Technical support available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. Battery powered. Probe array, low frequency constant magnitude alternating current drive to probes and LCD display. The probes come in many types for embedding in new infrastructure, retrofitting to existing infrastructure, and a surface probe for more impromptu inspection. |

## F13.7 Bibliography

ASTM D-257 Standard Test Methods for DC Resistance or Conductance of Insulating Materials

ANSI/ESD STM11.11:2001—Surface resistance measurement of static dissipative planar materials

ANSI/ESD STM11.2:2000—Volume resistance measurement of static dissipative planar materials

# F14.0 Condition Assessment of Plastic Pipes

## F14.1 Overview

Assessing the condition of plastics pipelines requires different approaches to those used for cementituous and ferrous pipelines. This is because the degradation of plastics pipes with time is completely different from that of these other materials. The difficulty in assessing the condition of plastics pipes arises because they do not lose material from the pipe wall. Instead, fracture in plastic pipes occurs by crack initiation from defects either inherent in the pipe wall or damage sites at the pipe outer surface.

Non-destructive condition assessment for plastic pipes requires that sub-critical crack growth through the pipe wall be detected before ultimate fracture failure occurs. Currently no non-destructive techniques are available to locate cracks in plastic pipes before failure occurs. However, destructive condition assessment techniques can be used to assess the level of resistance to this kind of failure.

## F14.2 Main Principles

Failure of plastic pipes occurs by crack growth through the pipe wall. Depending on conditions and material, this can result in failure by short cracks that grow slowly through the pipe wall (the 'leak before break' scenario) or by brittle failure, where a whole pipe length can be completely fractured.

Currently, no non-destructive techniques are available to detect this type of sub-critical damage. However, several condition assessment techniques are available that use samples extracted from the pipe to measure important fracture properties. Although such tests are destructive and do not indicate the extent of sub-critical crack growth in the pipe wall, they do indicate how well the pipe material would resist such damage should it be initiated. Condition assessment techniques that can be used in this context are fracture toughness testing, gelation testing and slow crack growth resistance testing; see reviews of these techniques for more information.

The remaining service life of a specific asset can only be estimated based on the expected size of inherent defects in the pipe wall and damage at the pipe outer surface. Such estimates of inherent defects and damage size can be made from microscopic examination of similar pipes that have previously failed by fracture in service. Extensive experimental fracture property data has been published in the literature, which indicates the expected material properties (strength etc) for well-manufactured and poorly manufactured plastic pipes. Comparing measured values from pipe samples with this published data may indicate an inferior section of pipe.

Material quality data can be used in conjunction with known service conditions to predict the likely remaining life of pipes in a population of assets. Stochastic models can be utilized in this analysis.

## F14.3 Application

The current techniques used to assess plastic pipes are only able to assess the quality of plastic pipes. The lifetime of a plastic pipe is dependant on a number of factors, such as pressure and external loads, which can be measured, and on defect size, which cannot. As defect size can only be measured after failure the remaining life predictions can only be applied to a batch of assets using stochastic allocation of defect size and not to a specific asset.

## F14.4 Practical considerations

- The material properties of a plastic pipe sample will give a quantitative assessment of physical parameters, but can only be used to give a qualitative indication of its likelihood of failure. An assessment of failed plastic pipes can be conducted to assess the quality of pipes that have already been exhumed.
- For reactive assets (such as distribution mains), statistical analysis of failure data provides a more practical approach to the identification of problem assets.

## F14.5 Advantages

- Condition assessment of samples from important assets could provide information that would prevent an expensive and unforeseen failure.

## F14.6 Limitations

- Condition assessment of plastic pipes is currently very difficult, as no techniques are available to give the remaining service life of an individual pipe.
- Approaches available are destructive and can only give a relative measure of pipe quality; for example, material properties of the sample in comparison to industry benchmarks.
- Gathering field samples for testing will cause a disruption to service while taking such samples.

**Table F-15. Summary Condition Assessment of Plastic Pipes.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes. |
| | Material type | Plastic. |
| | Service area | Potable and wastewater. |
| | Access requirements | Pipe samples must be exhumed for testing. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Currently all plastic assessment tests are destructive. |
| | Interruption to supply/function | Pipes must be exhumed for testing. |
| Technical suitability | Assessment parameters | Material properties of pipe sample. |
| | Integration with software tools | N/A |
| | Commercialization of tool | Tests are conducted to Standards; see specific test review for details. |
| | Previous/existing use of the tool in sector | see specific test review for details. |
| | Accuracy/reliability | Relative measure of pipe ‘quality’. |
| | Ease of validation of results | Direct measurements. |
| Utility technical capacity | Asset management sophistication required | Could be used by any utility. |
| | Skills required (level of tool sophistication); usability | Specialized test house. |
| | Technology required (level of tool sophistication) | Specialized test house. |
| | Documentation | See specific test review for details. |
| | Availability of technical support | See specific test review for details. |
| Economic factors | Cost per inspection | See specific test review for details. |
| | Resource requirements | See specific test review for details. |

## F14.7 Bibliography

References for the tools used for the condition plastic pipe can be found in their reviews:

- Fracture Toughness C-Ring Testing
- DSC Gelation Assessment
- Methylene Chloride Gelation Assessment
- Slow Crack Growth Resistance

# F15.0 Core/Coupon Sampling

## F15.1 Overview of Inspection Tool

Core/coupon sampling is a method for obtaining small samples on which to conduct testing. The samples obtained by this method are small enough so that pipes can be repaired using repair clamps. As such, while it is not destructive to the pipe, it does require repair work to be conducted.

## F15.2 Main Principles

Core/coupon sampling is conducted when a test is to be carried out that requires only a small piece of the asset or asset material. Sampling can be conducted on any pipe type and material with the exception of vitrified clay pipes due to its brittle nature.

If the required sample size is such that its removal can be repaired by normal repair techniques, such as clamping, the pipe is exposed, the sample cut from the pipe wall, and the pipe then repaired. If the sample size required is too large to allow clamping type repairs, cut-out sampling may be required (see Cut-out Sampling review).

Core and coupon sampling are similar with the exception that core samples are generally removed using a drill (cylindrical through wall sample), while coupons are cut from the wall and can be any size without being fully circumferential. These samples can be used for phenolphthalein testing, carbonation testing, pit depth measurement and other tests depending on the pipe material.

## F15.3 Application

Core/coupon sampling is used to obtain a sample from the wall of any pipe type. The core/coupon removed can then be tested using techniques appropriate to the material. Core sampling can also be undertaken on civil assets.

- No standards are available to which reference this technique.

## F15.4 Practical considerations

- Core/coupon sampling is widely used and simple to conduct.
- Often core/coupon samples can be obtained during normal work practice, such as when a new connection is made to a water pipe; the section removed can be used as a core sample.

## F15.5 Advantages

- Samples can be obtained without removing a section of pipe and so does not require extensive repair work.
- Core/coupon samples can be obtained during normal work practice.
- In the case of core samples, samples can be obtained from water pressure pipes without interrupting service using under pressure tapping techniques.

## F15.6 Limitations

- Samples taken can only be used for a limited range of tests.
- Due to small sample size, samples may not be representative of the entire pipe circumference nor the condition along the pipeline.

**Table F-16. Summary Core/Coupon Sampling.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes and civil assets. |
| | Material type | All except VC. |
| | Service area | Potable and wastewater. |
| | Access requirements | Access to pipe surface is required and access for tapping machine. |
| | Limitations relating to asset condition | If pipe in poor condition, may not be suitable to take coupon, this could induce a stress concentrator. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Sampling technique, not destructive to pipe but does require repair work to be conducted. |
| | Interruption to supply/function | Pressure pipes must be taken off-line before sampling, unless sample (tapping) can be made under-pressure. |
| Technical suitability | Assessment parameters | N/A |
| | Integration with software tools | None. |
| | Commercialization of tool | Contractor services could be used. |
| | Previous/existing use of the tool in sector | Industry collects coupons but these are underutilized for analysis. |
| | Accuracy/reliability | N/A |
| | Ease of validation of results | Direct measurements. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Sample as required for installing pipe connections and basic repairs. |
| | Technology required (level of tool sophistication) | Low. |
| | Documentation | WSAA under pressure tapping code. |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | Varies with the size of coupon and pipe. |
| | Resource requirements | Crew as required for installing pipe connections and basic repairs. |

# F16.0 Corrosion Burial Testing

## F16.1 Overview

Corrosion of metals in disturbed soils, such as occurs when pipes are laid in trenches, is complex and not fully understood. Burial testing is used to give an indication of soil corrosivity assessed over time, rather than as a snap shot as is obtained from most test methods.

This type of testing is conducted by burying multiple samples near a pipeline, which are then exhumed incrementally over several years to give an indication of soil corrosivity that takes into account the seasonal and other variations that the pipe is subject to. This method allows corrosion measurements to be undertaken without destructive sampling from the pipeline of interest.

## F16.2 Main Principles

While tests such as soil resistivity (see Soil (electrical) Resistivity review) and pH are useful for indicating the corrosivity of a soil, they do not capture the variation in corrosivity to which a pipeline is exposed over time. In order to determine the corrosivity of a soil taking into account these variations, burial testing can be used in which multiple samples are exposed to the same corrosive environment as the pipe over extended time periods.

Burial testing is conducted for metallic pipes, generally ferrous materials, by burying several samples of the same material as the pipeline. The samples are then exhumed over time and examined to assess the level of corrosion.

By comparing samples exhumed over multiple years, an indication of corrosion and pitting rates can be obtained. It should be noted that due to differences in geometry these samples only indicate corrosion rate and do no give the actual corrosion the pipe is subject to at its outer surface.

## F16.3 Application

Burial testing is conducted to obtain an understanding of soil corrosivity over time, rather than a ‘snapshot’ measurement technique. This testing can be conducted for any asset type, however is generally limited to ferrous assets without protective coatings.

## F16.4 Practical considerations

- The samples should be buried near to and at a similar depth as the pipeline in an effort to ensure that environmental conditions of the samples are as similar as possible to those of the pipeline.
- If the pipeline of interest includes welds, then the test samples should also include welds so that the samples are representative of the pipeline.
- When multiple samples are to be exhumed at the same time, they should be connected with a polymeric rope to aid location.

## F16.5 Advantages

- As testing takes place in real time under real conditions, the results represent corrosion conditions more accurately than tests which only provide a ‘snapshot’ of soil conditions.

## F16.6 Limitations

- In the vast majority of pipelines where corrosion is causing problems, the nature of the corrosion damage is not uniform along the pipeline. Often this is also true along a single pipe length, limiting the value of results obtained from burial samples.
- Corrosion burial testing needs to be planned prior to installation of the pipe for optimal results.
- As there are geometrical, time and location variations between the burial sample and the actual pipe, results from the sample may not represent the actual corrosion rate at the pipe outer surface.
- Burial testing is a long term test method where results are obtained over many years; samples need to be buried for extended periods before useable results can be obtained.

**Table F-17. Summary Corrosion Burial Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipe. |
| | Material type | Generally ferrous. |
| | Service area | Potable and wastewater. |
| | Access requirements | None. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | Generally applicable to large diameter mains, but no inherent restrictions. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Asset on-line. |
| Technical suitability | Assessment parameters | Corrosivity of the soil environment. |
| | Integration with software tools | None. |
| | Commercialization of tool | N/A |
| | Previous/existing use of the tool in sector | Not a common practice in the water sector. |
| | Accuracy/reliability | Relative assessment. |
| | Ease of validation of results | Validation through assessment of pipe. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Skills associated with evaluation of test piece; depends on technique used. |
| | Technology required (level of tool sophistication) | Low. |
| | Documentation | N/A |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | Depends on technique used. |
| | Resource requirements | Samples must be exhumed. |

## F16.7 Bibliography

1. Korb, L., Olsom, D., Davis, J., Destefani, J., Frissell, H., Crankovic, G., Jenkins, D., Stedfeld, R., Mills, K., Johnson, J., Kiepura, R. and Humphries, D. *Metals Handbook, 9th edition Volume 13 – Corrosion*, ASM International, United States of America, 1987

# F17.0 Cover Meter - Reinforcement Location and Measurement

## F17.1 Overview of Tool

Cover meters are a non-destructive means for determining the depth to concrete reinforcement, the location of reinforcement at different depths up to 360mm, bar spacing and anchor setting points in concrete assets. Cover meters use the eddy current testing method.

## F17.2 Main Principles

Along with concrete quality, cover thickness is the single most important durability parameter for concrete structures.

In the pulse current method, a pulse of current transmits a magnetic field through the reinforcement. Following the pulse, an eddy current induced in the reinforcement bar produces a second magnetic field that creates a decay time signal in the coils proportional to the bar size and cover. Coils housed in the cover meter tool's measuring head can be tuned for sensitivity to bar spacing or cover depth. The pulse current method can be combined with a scan car that measures the position of the measuring head relative to the concrete surface.

Some cover meters have a built-in facility to measure half-cell potential measurements as well as the Eddy current method. The combination of both methods results in accurate surveys of reinforcement in concrete structures. BS1881:242 stipulates accuracy requirements for cover meters when measuring in different ranges. Advanced cover meters have an accuracy within ±1 mm.

## F17.3 Application

Cover meters can be used on concrete slabs, walls, columns, pipes and spiral mesh.

- British Standard BS1881:242

## F17.4 Practical Considerations

- Cover meters are sophisticated tools that come in digital versions, and calculate and display the location of reinforcement instantaneously. Their operation is menu driven with on-screen guidance. Generally logged data is date and time stamped. Results are downloadable to PC or printer.
- Some tools are designed for large scale and detailed investigations, and have a range of cover functions incorporated in their program. These allow a comprehensive range of characteristics and logging of up to 30,000 measurements.
- Many cover meters display the location of reinforcement in large black characters on a LCD that can be backlit in poor light conditions.

## F17.5 Advantages

- Non-destructive methods for checking cover have become faster and more accurate in recent years.
- Cover meters are more accurate for determining the penetration depth of the carbonation front than the traditional method of dye penetration where a freshly fractured surface is sprayed with a pH indicator, such as phenolphthalein or thymolphtalein.

## F17.6 Limitations

- Cover meters lose accuracy at greater depths. Even 'long range' cover meters can only be relied upon to detect rather than measure bars at depths between 250 and 300mm; and this is subject to bar size.

**Table F-18. Summary Cover Meter – Reinforcement Location and Measurement.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Concrete elements such as slabs, beams, columns, walls, pavements, tunnels, pipes and dams. |
| | Material | Reinforced concrete. |
| | Service area | Potable or wastewater. |
| | Access requirements | Direct contact with asset. |
| | Limitations relating to asset condition | No limitations relating to asset condition. |
| | Limitations relating to asset size/geometry | No limitations relating to size/geometry: the maximum thickness of concrete which can be tested is 300mm. Cover meters measures to over 250mm depth and detect to over 300mm, subject to bar size. |
| | Continuous/discrete | Continuous readings in time and space. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | The asset can remain in use; needs to be taken off-line only if an internal surface is required to be accessed. |
| Technical suitability | Assessment parameters | Cover depth to reinforcement, location of reinforcement at different depths up to 360mm, bar spacing and anchor setting points. |
| | Integration with software tools | Can be integrated with software tools. |
| | Commercialization of tool | Equipment is widely available from selected commercial vendors. |
| | Previous/existing use of the tool in sector | Widespread use in the water and other sectors, and acceptable to stakeholders. |
| | Accuracy/reliability | Advanced cover meters have an accuracy within ±1mm. |
| | Ease of validation of results | Results can be validated. Some cover meters have a built-in facility to measure half-cell potential measurements as well as the Eddy current method. The combination of using both methods results in accurate surveys of reinforcement in concrete structures. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy to use by following simple procedure. Measurements can be taken by unqualified staff. |
| | Technology required (level of tool sophistication) | Cover meters are sophisticated tools which come in digital versions which calculate and display the location of reinforcement instantaneously. |
| | Documentation | Cover meters are thoroughly documented British Standard BS1881:242. |
| | Availability of technical support | Technical support widely available. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. Battery powered. Resources required can also depend on asset being inspected. Buried assets need to be exposed. |

## F17.7 Bibliography


1. BS 1881 Part 204:1988: Recommendations on the Use of Electromagnetic Covermeters.
2. BS1881:242 British Standard 1881

# F18.0 Crack Measurement Tools

## F18.1 Overview of Tools

Cracks in concrete structures can be measured with a range of tools. Crack measurement tools and their corresponding measuring ranges and accuracies are listed below.

## F18.2 Main Principals

**Deformation Meters**: Deformation Meters are used for measuring linear deformations, cracks, settlements and shrinkage coefficients. Two base plates are attached to the concrete to give fixed reference points approximately 300 mm apart. The gauge is then used to accurately measure the change in length as the structure ages. Deformation meters can have a measuring length of 300 mm. They are two versions of dial gauges: analog 5 mm x 0.001 mm and digital 25 mm x 0.001 mm. The meters include a setting and calibration bar, base plates and adhesive.

**Measuring Magnifier**: The measuring magnifier typically has a magnification of 8×. Crack widths are normally limited to 0.2mm or 0.3mm in concrete structures. This crack width measuring device enables accurate determination of whether cracks exceed this limit.

**Crack Width Meter**: The crack width meter is used as a comparator to give an approximate crack size during visual surveys. Combined with 10 reduction scale rules.

**Crack Monitor**: The crack monitor is used on structures where the rotation at cracks is also significant. The crack monitor gauge is specifically designed to measure rotation, transverse and longitudinal movement. Special fittings are available to measure external and internal corners.

## F18.3 Application

Crack measurement tools can be applied to a wide range of substrates including steel. They are most commonly used on concrete structures.

- ASTM E1457-00 Standard Test Method for Measurement of Creep Crack Growth Rates in Metals

## F18.4 Practical Considerations

- Crack measurement tools are widely used for the condition assessment of concrete structures and can be purchased for a number of commercial suppliers. The tools are easy to use and often handheld.
- When measuring crack widths with deformation meters, it is important to measure across the crack and across adjacent intact concrete so that adjustment to the crack width movement can be made.
- Table F-19 gives a summary of the tools.

**Table 19. Summary of Tools.**

| CRACK MEASUREMENT TOOL | ACCURACY/ MEASURING RANGE |
|---|---|
| Deformation meter | Accuracy ± 0.001mm. |
| Measuring magnifier | Magnification 8x Measuring range 15 mm x 0.05 mm. Accuracy ± 0.05mm. |
| Crack width meter | Graduations from 0.05 – 5 mm. |
| Crack monitor | Measuring scale for horizontal and vertical measurements: horizontal ± 25 mm and vertical ±10 mm.<br>Reading accuracy of ±1mm on grid and ± 0.1 mm with a caliper. |

## F18.5 Advantages

- Crack measurement tools are accurate, reliable, non-destructive, easy to use, relatively inexpensive and very portable.

## F18.6 Limitations

- Results are likely to vary according to changes in parameters such as the water level in concrete tanks and temperature of concrete due to exposure to sunlight and seasonal variation.

**Table F-20. Summary Crack Measurement Tools.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Reinforced concrete structures such as dams, walls tanks, large pipes, buildings, etc. |
| | Material type | Most commonly used on reinforced concrete. |
| | Service area | Potable or wastewater. |
| | Access requirements | Direct contact with surface of asset. If asset is buried then it must be exposed. |
| | Limitations relating to asset condition | Generally no restriction. However surface may need cleaning in order to accurately locate edges of cracks. |
| | Limitations relating to asset size/geometry | No limitations relating to size of concrete element. |
| | Continuous/discrete | Discreet readings. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | The asset can remain in use and does not need to be taken off-line. |
| Technical suitability | Assessment parameters | Crack width. Rotational, transverse and longitudinal movements at any point on a structure where there is crack movement can also be measured. |
| | Integration with software tools | The majority of tools are stand alone. |
| | Commercialization of tool | Equipment is fully developed, available from a wide range of commercial vendors and can be used off the shelf. |
| | Previous/existing use of the tool in sector | Widespread use internationally in the water industry. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Direct measurement easily validated. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Relatively easy to use by following simple procedure. Crack measurement tools do not require specialist knowledge or training. |
| | Technology required (level of tool sophistication) | Range from low to moderate level of sophistication. |
| | Documentation | ASTM E1457-00. |
| | Availability of technical support | Technical support widely available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. |

## F18.7 Bibliography

1. ASTM E1457-00 Standard Test Method for Measurement of Creep Crack Growth Rates in Metals

# F19.0 Current Monitoring

## F19.1 Overview

Current monitoring is a non-destructive on-line condition assessment method that can be used on assets that contain electric motors. By monitoring variations in current flow the onset of electrical faults can be identified before equipment breakdown occurs. Current monitoring analysis can be used to detect electric motor problems such as broken rotor bars, broken/cracked end rings, flow or machine restriction and machinery misalignment.

## F19.2 Main Principles

This technique involves monitoring the current flowing through one of the power leads located at the motor control center or starter, typically by using a clamp-on ammeter. By measuring the electrical current variations and trending the recorded data over time, changes in the equipment operating conditions and performance can be monitored and compared to the design loads recorded during commissioning. The data can then be used for determining the onset of electrical faults or equipment breakdown.

The clamp-on ammeter (also known as Tong Tester) measures current by the strength of the magnetic field around it rather than by becoming part of the circuit. One modern method uses a small magnetic field detector device called a Hall-effect sensor. Hall-effect devices produce a very low signal level and thus require amplification.

The clamp on ammeter makes for quick and safe current measurements, because there is no conductive contact between the meter and the circuit.

## F19.3 Application

The technique of current monitoring can be used on electrical induction motors, synchronous motors, compressors, pumps and motor operated valves, to determine changes in the level of performance that occur over time and enable repair or replacement prior to electrical faults or equipment breakdowns occurring.

- There is no specific standard for test method.

## F19.4 Practical Considerations

- Current monitoring is a technique widely used for condition monitoring and can be easily undertaken on all electrical motors by a trained electrical technician or engineer using a hand held testing apparatus.
- Clamp-on ammeters are widely available from numerous suppliers; older units can only be used on AC equipment while newer equipment can measure both AC and DC. The older probe consists of a core of ferromagnetic material, which when closed forms the core of a transformer of which the wiring passing through the clamp is the primary winding.
- The least expensive clamp on ammeters use an average-detecting rectifier circuit that is then calibrated to read in RMS units; it is assumed in their design that the current is a sine wave of the local mains frequency, that is, either 50 or 60 Hz. When such meters are used with non-sinusoidal loads such as electronic equipment, the readings produced can be quite inaccurate. Meters that use true-RMS converters give accurate readings in almost any situation.
- Hall-effect sensor gives accurate readings over a wider frequency range from DC to thousands of hertz.

- The sensitivity of portable clamp-on ammeters is often dependant on cost, however most units can measure current flow with high accuracy.

## F19.5 Advantages

- Monitoring can be undertaken with the equipment on-line with minimal disruption.
- Routine current monitoring enables determination of equipment electrical faults prior to failure.

## F19.6 Limitations

- Trained electrical technicians are required to undertake assessment, as equipment must be under load to enable for reliable results.
- While the results obtained typically indicate that a possible problem is present, further analysis required to identify the exact equipment or component fault.

**Table F-21. Summary Current Monitoring.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Any electrical load. |
| | Material type | N/A |
| | Service area | Potable or wastewater. |
| | Access requirements | None. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Continuous in time. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Must be on-line with suitable precautions taken against operator direct contact with live parts. |
| Technical suitability | Assessment parameters | Current. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Fully developed and off the shelf. |
| | Previous/existing use of the tool in sector | Standard industry practice. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Electrician will already be trained to use. |
| | Technology required (level of tool sophistication) | N/A |
| | Documentation | Well documented. |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | Low; one person no more than a few minutes per load. |

## F19.7 Bibliography

1. Weschler instruments, http://www.weschler.com, accessed 2006

## F20.0 Cut-out Sampling

### F20.1 Overview

Cut-out sampling is a method for obtaining a short pipe ring sample on which a range of tests can be undertaken. It is a destructive technique that can be applied to pipes of any material, but is more generally used on smaller diameters.

### F20.2 Main Principles

Cut-out sampling is conducted when a pipe asset is to be assessed with a test that requires only a small section of the asset. The length of pipe removed is dependant on the test to be conducted. Sampling can be conducted on any pipe type and material; however it is unlikely to be conducted on vitrified clay pipes due to its brittle nature.

If the sample required is not a ring sample and is small enough so that the area could be repaired using a clamp type repair, then core/coupon sample may be a better option (see Core/Coupon Sampling review).

Samples obtained can be used in compressive strength testing, pit depth measurement, fracture toughness testing and other tests depending on the pipe material.

### F20.3 Application

Cut-out sampling is used to obtain a short pipe length for testing from the wall of any pipe type. The cut-out removed can then be tested to assess the pipe it was removed from. It is more generally used for assessment of water distribution pipes, but could be applied to wastewater pipes. No Standards are available to which reference this technique.

### F20.4 Practical considerations

- Cut-out sampling is widely used and simple to conduct.
- When obtaining samples from wastewater pipes the emptying of the pipelines and storage of sewage during sampling are important considerations.

### F20.5 Advantages

- Samples can be obtained without removing a full pipe length section of pipe, thereby minimizing repair work.
- Most condition assessment tests can be conducted on cut-out samples.

### F20.6 Limitations

- The sample obtained may not be representative of the condition along the pipeline entire pipe.
- Pipes must be taken out of service and pressure pipes emptied to allow sampling.

**Table F-22. Summary Cut-out Sampling.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes. |
| | Material type | All. |
| | Service area | Generally potable. |
| | Access requirements | Access to pipe surface is required. Pipeline to be depressurized. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Sampling technique, which requires repair work to be conducted. Destructive. |
| | Interruption to supply/function | Pipes must be taken off-line. |
| Technical suitability | Assessment parameters | N/A |
| | Integration with software tools | None. |
| | Commercialization of tool | N/A |
| | Previous/existing use of the tool in sector | Technique has been widely used in industry. |
| | Accuracy/reliability | Direct measurement. |
| | Ease of validation of results | N/A |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Sample as required for conducting pipe repairs. |
| | Technology required (level of tool sophistication) | Low. |
| | Documentation | N/A |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | Varies dependant on location, size, type, etc. |
| | Resource requirements | Crew as required for conducting pipe repairs. |

## F21.0 Drop Test

### F21.1 Overview

Water loss control programs are widely used throughout the water industry (see Leak Detection review). Drop tests are a simple non-destructive method for identifying areas of a network containing significant leakage.

A drop test can be undertaken for individual pipelines both new (at the time of installation) and old, small pipe network areas and larger areas. Drop tests work by isolating the area of interest and observing either the level of water in a reservoir or water pressure. Loss of water head/height (beyond normal use if all connections cannot be closed) indicates that either the pipe(s) or valve(s) are leaking. Similar testing has also been used to measure exfiltration in sewers.

Leak detection gives both an indication of condition and performance of the asset, depending upon the amount of leakage on a section of pipe. However, it does not give detail regarding the overall condition of the pipe.

### F21.2 Main Principles

The drop test involves isolating a section of pipe or pipe network and observing whether water is lost during the test. If the upper end of the pipeline is fed by a reservoir, as in a gravity-fed system, the level in the reservoir can be monitored. If this level drops during the test, the level of leakage can be determined by calculating the volume lost from the reservoir.

If the pipeline is not fed by a reservoir, leakage can be identified by monitoring the pressure associated with the falling water level in the pipeline. When the section has been isolated, a pressure monitor fitted below the uppermost water level will enable any drop in the level of the water to be detected.

### F21.3 Application

Drop tests are generally applied to detect leakage in large diameter transmission mains, or area of a network. They can also be applied to sewerage assets to assess exfiltration.

- There are no known Standards which reference drop testing.
- Practical considerations
- As a general approach to assessing water tightness, drop testing can be undertaken by any utility. The simple nature of the test has let it to be widely used in the water and other industry sectors. It has been used in the U.K. water sector as a low technology approach to assessing leaks in transmission mains. It has also been used in research to assess the level of exfiltration from sewers.
- The accuracy of drop testing is limited by the type of method used to assess leakage (level or pressure drop) and the size of the area being tested.
- Advantages
- Low tech approach for assessing leakage within pipelines. This technique can also be applied to pipe sections.
- The drop test can be used to gain a quantitative measure of leakage for a pipe or area of the network.

## F21.4 Limitations

- The time involved in isolating pipe sections and monitoring the reservoir makes this method impractical except on an annual basis.
- Only the presence of leaks is indicated, no indication is given of location. Leaks can be associated with the down stream valve.
- The drop test requires assets to be taken off-line.
- The test does not give detail regarding the overall condition of the pipe.

**Table F-23. Summary Drop Test.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipelines. |
| | Material type | Any. |
| | Service area | Potable or wastewater. |
| | Access requirements | Requires ability to isolate pipeline and access to monitoring points and/or service reservoirs. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | Large diameter pipelines. |
| | Continuous/discrete | Discrete measurement in time. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Asset be taken off-line. |
| Technical suitability | Assessment parameters | Water loss from pipe either due to exfiltration (gravity sewers) or leakage (pressurized pipes). |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | General approach. |
| | Previous/existing use of the tool in sector | Used in the UK for leak assessment on transmission mains, used in Australia for assessment of exfiltration. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Technical skills associated with pipeline management . |
| | Technology required (level of tool sophistication) | Low tech. |
| | Documentation | No. |
| | Availability of technical support | No. |
| Economic factors | Cost per inspection | Depends on test. |
| | Resource requirements | Depends on test. |

## F22.0 Ductor (Micro Ohm Resistance) Testing

### F22.1 Overview

The Ductor (proprietary name) test is a non-destructive assessment to determine the contact resistance in draw–out contacts such as circuit breakers on high current devices and bus bar interconnections located in electrical power distribution boards and switchboards. The test is normally carried out by applying a high current across the device which is being assessed, allowing the detection and isolation of a poor connection so that corrective action can be undertaken.

### F22.2 Main Principles

Typically the four-wire Kelvin Bridge method is used consisting of two current and two voltage wires. The two current leads are connected across the joint to be tested. A high current (typically 0-600A) is passed through the joint or contact under assessment at a low voltage (0-4V DC). The two sensing leads measure the voltage across the joint. The resistance is calculated from the test current and sense voltage, with the resistance measured in micro Ohms ($\mu\Omega$).

The voltage sensor leads are in parallel to the joint and only carry a miniscule current. As such, the test lead resistance can be ignored.

The test can determine the condition of switch gear and circuit breakers, which can deteriorate over time as a result of heat build up and the formation of carbon deposits during operation. Surface contamination, overloading with resultant heat build up or incorrect torque settings can also result in poor quality joints.

### F22.3 Application

The Ductor assessment method is commonly undertaken to determine the condition of electrical circuit breakers contacts, switchgear contacts, cable joints and bus bars joints where high currents are encountered. It is commonly used on new installations for initial verification and benchmarking, followed by periodic tests.

- There is no specific standard for test method.

### F22.4 Practical Considerations

- Ductor test assessments should be conducted by trained electrical technicians or engineers with experience in undertaking diagnostic analysis of electrical equipment and components.
- Auxiliary supply voltage to the test unit is typically 100 – 250V AC. The duration of output current is limited (dependant upon manufacturer) but need only be long enough to get a steady reading. For repetitive tests, cool off intervals may be required. Test equipment with download facilities are available.
- When assessing new equipment/joints, knowledge of the materials electrical properties is required. This may be the manufacturer's stated contact resistance or the conductivity of the bus bar material.
- For periodic testing, previous assessment results, typically those obtained during commissioning, are required for comparison in order to determine the current condition and likelihood of future equipment breakdown.

- Access to epoxy resin filled cable joints is not possible. The equipment to be tested must be electrically isolated and accessible.
- A higher test voltage than that specified above is not required nor is it desired. Higher voltages can break down the joint resistance.

## F22.5 Advantages

- Ductor test assessments are sensitive and provide measurements of micro Ohms (μΩ).

## F22.6 Limitations

- Prior to undertaking Ductor testing, the equipment being assessed must be isolated.
- Previous test results are required to assess the current condition of the asset.

**Table F-24. Summary Ductor (Micro Ohm Resistance) Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Electrical connections, busbars and contacts. |
| | Material type | The conductor. |
| | Service area | Potable and wastewater. |
| | Access requirements | Access to normally livened parts which must be made dead. Portable hand held equipment. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete reading. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Off-line. |
| Technical suitability | Assessment parameters | Resistance. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Off the shelf. |
| | Previous/existing use of the tool in sector | Widely used. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Qualified electrician. |
| | Technology required (level of tool sophistication) | Test instrument only. Data requires no further manipulation. |
| | Documentation | Well documented. |
| | Availability of technical support | Commercially available. |
| Economic factors | Cost per inspection | Labor costs only. |
| | Resource requirements | One person, typically two hour period/switchboard. |

## F22.7 Bibliography


1. T&R test equipment, http://www.trtest.com, accessed 2006
2. Transpower homepage, http://www.gridupgrade.co.nz, accessed 2006

## F23.0 Electrical Potential (Half Cell) Measurement of Concrete Reinforcement

### F23.1 Overview of Tool

Electrical potential measurement is a non-destructive technique that can be used to identify areas of reinforced concrete in need of repair or protective treatment before corrosion causes cracking and spalling. It does this by measuring the electrical potential between the reinforcing and a reference electrode at the surface. By taking regular measurements, the behavior of new and relatively new structures can be monitored and maintenance costs minimized.

### F23.2 Main Principals

Steel corrosion is an electrochemical process involving anodic (corroding) and cathodic (passive) areas of the metal. To measure the electrical potential, an electrical connection is made to the steel reinforcement of the asset to be assessed. This is connected to a high impedance digital millivoltmeter, often backed up with a data logging device. A standard reference electrode, either copper/copper sulfate or silver/silver chloride half cell, is also connected to the millivoltmeter. The electrode used has a porous connection at one end that can be touched to the concrete surface, see Figure F-3. The millivoltmeter will then register the corrosion potential of the steel reinforcement nearest to the electrode's point of contact. By measuring results on a regular grid and plotting results as an equipotential contour map, areas of corroding steel may readily be seen. Using 3D mapping techniques, a more graphical representation of the corrosion can be shown.

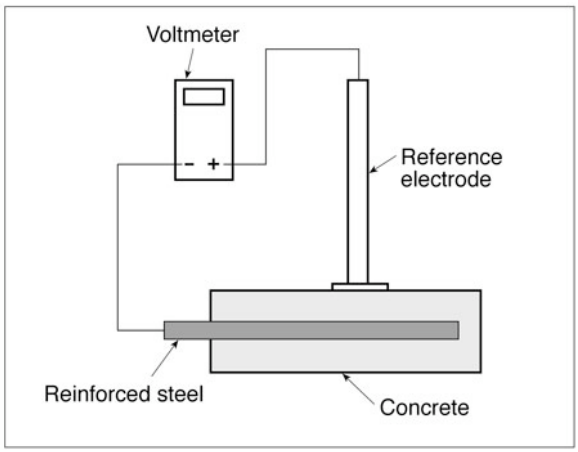


**Figure F-3. Electrical Potential Measurement Technique.**
**(Reprinted with permission from: Gu, P. and Beaudoin, J, 1998).**

### F23.3 Application

Electrical potential measurement is used to assess the corrosion potential of steel reinforcement in civil concrete assets.

- ASTM Standard C876 provides general guidelines for evaluating corrosion in concrete structures. Electrical potential measurement is also referenced in BS 1881: Part 201.

### F23.4 Practical Considerations

- Equipment typically has a large digit display which is backlit for ease of reading in poorly lit environments.
- Extensible probe holders are available for remote surveying.

- Many different electrode configurations have been tried in practice and several of these have been found to have advantages over standard arrangements.
- Surfaces in excess of 4000$m^2$ can be measured.
- The reinforcement at the point of measurement has to be electrically connected to the millivoltmeter for reliable results to be obtained. If multiple sheets of reinforcement were used and not electrically connected a point of contact must be made to each sheet.
- Electrical potential measurement equipment typically readily portable and consists of electrode rods or wheel, connecting cables and display unit.

## F23.5 Advantages

- Electrical potential measurement is a safe, rapid, cost-effective and non-destructive method of condition assessment, which offers key information on the evaluation of corrosion.
- It is the simplest way to assess the severity of steel corrosion, as it measures corrosion potential, which is qualitatively associated with steel corrosion rate.
- Confidence in electrical potential measurement as an indication of corrosion potential has developed greatly as a result of bridge deck corrosion surveys. An indication of the relative probability of corrosion activity was empirically obtained through measurements during the 1970s.
- According to the ASTM C876 method, corrosion can only be identified with 95% certainty at potentials more negative than -350 mV. However experience has shown that passive structures tend to show values more positive than -200 mV and often positive potentials. Potentials more negative than -200 mV may be an indicator of the onset of corrosion. The patterns formed by contours on graphical representations of corrosion can often be a better guide than single potential readings in these cases.

## F23.6 Limitations

- Electrical potential measurement does not directly indicate the rate of corrosion. There are difficulties associated with making reliable quantitative measurements. The factors influencing the electrical potential measurements are affected by the resistivity of the concrete and the pH of the pore solution (carbonation). It could be necessary to use a statistical analysis of measurements on individual structures to establish areas where corrosion of reinforcement occurs.
- Several factors can alter the precision of potentials measured:
  - Concrete cover depth
  - Concrete resistivity
  - High resistive surface layers
  - Polarization effects
  - Organic coatings and sealers
  - Concrete patch repair
  - Epoxy coated and galvanized reinforcement
  - Use of corrosion inhibitors
  - Chloride ion concentration
  - Carbonation
  - Oxygen concentration

- These factors influence electrical potential readings because when surface potentials are taken they are measured remotely from the reinforcement due to the concrete cover. The potentials measured are therefore affected by the potential drop over the distance between the reinforcement and the electrode.
- Electrical potential measurement cannot be used on structures with active cathodic protection systems. An energized cathodic protection system and stray current will make electrical potential measurements meaningless.
- Electrical potential measurement should never be used in isolation. It should be combined with the measurement of the chloride content of the concrete and its variation with depth and also the cover to the steel and the depth of carbonation.

**Table F-25. Summary Electrical Potential (Half Cell) Measurement of Concrete Reinforcement.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | All reinforced concrete assets. |
| | Material type | Reinforced concrete. |
| | Service area | Potable and wastewater. |
| | Access requirements | Direct contact with asset. If asset is buried then it must be exposed, surface coatings do not need to be removed. |
| | Limitations relating to asset condition | No limitations relating to asset condition. |
| | Limitations relating to asset size/geometry | No limitations relating directly to geometry. There are limitations relating thickness of concrete. With increasing concrete cover, the potential values at the concrete surface over actively corroding and passive steel become similar. Thus the location of small corroding areas becomes increasingly difficult. |
| | Continuous/discrete | Continuous readings in time and space. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | The asset can remain in use and does not need to be taken off-line unless an internal surface is required to be accessed. |
| Technical suitability | Assessment parameters | Detection of corrosion. |
| | Integration with software tools | Can be integrated with software tools to produce potential mapping: equipotential lines that allow the location of the most corroding zones at the most negative values. |
| | Commercialization of tool | Equipment is widely available from selected commercial vendors. |
| | Previous/existing use of the tool in sector | Widespread use on bridge deck corrosion surveys. Use increasing in the water sector, gradually becoming acceptable to stakeholders. |
| | Accuracy/reliability | Corrosion can be identified with 95% certainty at potentials more negative than -350 mV. |
| | Ease of validation of results | For validation purposes, electrical potential measurement can be combined with the measurement of the chloride content of the concrete and its variation with depth and also the cover to the steel and the depth of carbonation. |

| | Criteria | Assessment |
|---|---|---|
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy to use by following simple procedure. Measurements can be taken by unqualified staff. |
| | Technology required (level of tool sophistication) | Sophisticated digital tools. For many tools, measurements are automatically converted and displayed as equipotential lines that allow the location of the most corroding zones at the most negative values potentials. |
| | Documentation | ASTM C876 and BS 1881:Part 201. |
| | Availability of technical support | Technical support widely available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. Battery powered. Resources required can also depend on asset being inspected. Buried assets need to be exposed. |

## F23.7 Bibliography


1. Gu, P. and Beaudoin, J., *Obtaining Effective Half-Cell Potential Measurements in Reinforced Concrete Structures*, Construction Technology Update No. 18, pp1-3, July 1998
2. Naumann, J. and Haardt, P. NDT *Methods for the inspection of highway structures'. International Symposium* (NDT-CE 2003). Non-Destructive Testing in Civil Engineering, pp2-5, 2003
3. Torrent, R. and Frenzer, G. *A method for the rapid determination of the coefficient of permeability of the "Covercrete"*. International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE). pp985-992, 26-28.09.1995
4. ASTM Standard C876 provides general guidelines for evaluating corrosion in concrete structures
5. BS1881-201:1986 Testing concrete. Guide to the use of non-destructive methods of test for hardened concrete
6. Technical brochures produced by MG Associates Construction Consultancy Ltd, 2006

## F24.0 FailNet-Reliab

### F24.1 Overview

FailNet-Reliab is a hydraulic reliability model for water pipelines developed by the French research organization Cemagref. The approach is based on a hydraulic model (see Hydraulic Modeling review) of the network coupled with reliability analysis. The output is an assessment of the networks hydraulic performance expressed in terms of the ability to meet demand.

### F24.2 Main Principles

FailNet-Reliab is a computer modeling tool that can be used to assess the reliability of water distribution networks. Reliability is considered in the context of water demand satisfaction; essentially it is the quotient between the available consumption and the water demanded.

After a specific hydraulic modeling study, where available consumption is computed according to the pressure head at each node, several reliability indices are assessed and can be used as performance indicators. Different scales of assessment are undertaken:

- Pipes – the impact of a pipe break on all the nodes of the network.
- Nodes – the reliability of supply at the node in relation with all the links.
- Global network – the overall reliability of the network.
- The model is implemented in two steps:
- Firstly, a hydraulic model is constructed. This differs from a classical hydraulic model because water consumptions are not fixed and depend on computed pressure heads and water demands. The Newton-Raphson method is used to solve the hydraulic equations and compute the outputs.
- Secondly, reliability indices are assessed. The reliability indices depend on the results of the hydraulic models (with or without pipe breaks), on the weight of each nodes (quantity, vulnerability) and on pipe failure probabilities (which can be assessed with probability models, such as Failnet-Stat). The indices represent the volume of non-supplied water in the year because of failure risk.

### F24.3 Application

FailNet-Reliab is used to assess the reliability for water supply networks utilizing hydraulic models and failure probability estimates. This allows the reliability of a network to be improved by modeling to compare different asset management strategies.

### F24.4 Practical considerations

- The tool is not fully commercialized and the approach has only had limited use in France and with research groups.
- Data requirements are similar to that of classical hydraulic data. For nodes, altitude, water demand and type of water use are required. For pipes, the roughness, length and diameter are required. The volume and altitude are required for tanks.
- Failure probability, as calculated by FailNet-Stat (see FailNet-Stat review) can also be incorporated into the model, but is not mandatory.

- The software was to be reprogrammed in 2006/2007 to support all hydraulic features and to improve functionality.

## F24.5 Advantages

- Provides engineers with a different view of the networks hydraulic performance by factoring in reliability indices into the modeling process.

## F24.6 Limitations

- Has only had limited use in France and with research groups.
- FailNet-Reliab requires additional information such as failure probability and mean repair time to gain the full benefit from the package, and these have to be developed/determined separately.
- Some hydraulic features are not supported and may need to be replaced by equivalent sources/demands.

**Table F-26. Summary FailNet-Reliab.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Water pipes. |
| | Granularity | System and sub system level. |
| | Service areas | Potable |
| Technical suitability | Focus of analysis | Hydraulic reliability for water pipelines. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good data is available. |
| | Commercialization | Software available from Cemagref, France. Is not full commercial version. |
| | Previous/existing use of the tool | Only limited use in France and with research groups. |
| | Ease of validation | As for hydraulic modeling and reliability tools; independent validation is through field work. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Potable only; system or sub system level. |
| | Integration with other tools/GIS | CARE-W manager. |
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management. |
| | In-house skills required | Asset manager/engineer. |
| | Technology required | PC based tool. |
| | Documentation | Only limited documentation available. |
| | Data Requirements | Typical hydraulic modeling data is required. |
| | Linking to asset data | Pipe IDs. |
| | Availability of software and technical support | Software available from Cemagref, France |
| | Usability | Not fully commercialized. |

## F24.7 Bibliography

1. Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A-S., and Erickson, M. *Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems*, EPA, EPA/600/R-02/029, 2002

# F25.0 FailNet-Stat

## F25.1 Overview

FailNet-Stat is a failure forecasting model for water pipelines developed by the French research organization Cemagref. The approach uses historical data to define survival functions that are then used in Monte-Carlo analysis to forecast the number of failures within pipe cohorts.

## F25.2 Main Principles

FailNet-Stat is a computer modeling approach that is applied in three steps:

1. Analysis of historical failure records using a proportional hazard model. The system analyzes historical data, evaluates factors that influence failures, and identifies factors that maximize the likelihood of failures.
2. By incorporating the information above, the system uses a Weibull distribution to determine the time between successive failures. Separate models may be used for pipes grouped according to their material and number of previous failures.
3. Forecasting the number of failures for a defined period using a Monte-Carlo method. The system then forecasts the number of failures from the survival functions for each group of pipes (materials and current condition). This forecast can be used in combination with a hydraulic reliability model, in an economic model, or alone as one of the rehabilitation criteria.

## F25.3 Application

FailNet-Stat is designed to allow water authorities to establish failure probabilities for the various pipe materials in their water distribution system.

## F25.4 Practical considerations

- The tool is not fully commercialized and the approach has only had limited use in Europe and with research groups. It requires good quality asset data and failure history data. Furthermore, optimum usage of the tool requires experience, particularly with regards to the statistical significance of the results.
- An alternative model is being developed which is capable of producing better estimations of failure risk for individual pipes. This will form the basis of new software in 2007. The software will also facilitate result interpretation by incorporating a benefit index.

## F25.5 Advantages

- FailNet-Stat enables reliable failure probabilities to be established for a utility's water network (at individual pipe level), which can then be used to more effectively manage the network and undertake additional analysis functions such as reliability analysis, etc.

## F25.6 Limitations

- FailNet-Stat has only had limited use in Europe and with research groups. It requires good asset and failure data. Over-estimation of failure rates for individual pipes is common if the failure observation period is short. However, the relative failure risk is considered to be more accurate.

**Table F-27. Summary FailNet-Stat.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Water pipes. |
| | Granularity | System and sub system level. |
| | Service areas | Potable |
| Technical suitability | Focus of analysis | Failure forecasting model for water pipelines. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good data is available. |
| | Commercialization | Software available from Cemagref, France. Is not full commercial version. |
| | Previous/existing use of the tool | Only limited use in Europe and with research groups. |
| | Ease of validation | Statistical validation. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Potable only; system or sub system level. |
| | Integration with other tools/GIS | Through CARE-W Manager. |
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management. |
| | In-house skills required | Asset manager/engineer. |
| | Technology required | PC based tool. |
| | Documentation | Only limited documentation available. |
| | Data Requirements | Good asset and failure data is required. |
| | Linking to asset data | Pipe ID. |
| | Availability of software and technical support | Software available from Cemagref, France. |
| | Usability | Not fully commercialized |

## F25.7 Bibliography

1. Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A-S., and Erickson, M. Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems, EPA, EPA/600/R-02/029, 2002

# F26.0 Fiberscope Inspection

## F26.1 Overview

Fiberscope inspection works similar to CCTV inspection (see CCTC Visual Inspection review) but relies on optical fibers to gather images, which can be observed using an eyepiece. This technique can be used to inspect small diameter pipes and valves. One important feature is that fiberscope allows internal inspection of charged water mains. Fiberscopes are generally used to visually inspect a main for corrosion or sediment build-up. A camera can be attached to the eye piece of the fiberscope to record the inspection.

## F26.2 Main Principles

A fiberscope consists of three parts: 1) a steerable end for capturing imaging; 2) a viewing and control end; and 3) a flexible tube body.

The steerable end of the tool is manipulated by control wires that allow up to 120° of movement (depending on the specific tool used) and contains optical fibers for both lighting and image capture. The viewing and control end of the tool consists of an eye piece, which can also be attached to a CCTV or similar device to record the images, and controls that allow the tip to be manipulated and focusing.

Generally a 10 foot flexible tube will allow a pipe to be inspected for five feet on either side of the inspection point for corrosion, sediment build-up or other features of interest.

The tool can be inserted into empty or charged water mains via fire hydrants, air valves, tapping points and other similar access points.

The minimum size main that can be inspected is approximately 2½ inches. There is no specific maximum size, however flow through the main can affect positional control of the tool, and in larger diameter mains lighting may be insufficient for viewing the pipe internal surface.

## F26.3 Application

Fiberscope inspection is suitable for capturing visual images of the internal surface of water mains, primarily small diameter mains, and can be used to assess the condition of internal linings, the build up of corrosion products, and other features of interest. This technique can also be used for in-service inspection of valves.

## F26.4 Practical considerations

- Fiberscope inspection technology is widely available, easy to use and readily portable.
- It is used often in the aviation, power generation and other industries for inspection; however it is not widely used by water authorities who generally favor other techniques for obtaining data on the internal surface of pipes, such as physical inspection after exhumation.
- When conducting inspections in charged mains the flow through the main can affect controllability of the tool.
- The visual image needs to be analyzed manually, and so is dependant on image quality. The presence of particulate matter or bubbles will reduce image quality, potentially to a level that no useful information can be obtained.

## F26.5 Advantages

- Internal condition of water main assets can be inspected without exhumation.
- Tool allows for in service inspection of valves.
- Inspection can be conducted in charged mains; however the actual pressure allowable is dependant on the pressure rating of the product.

## F26.6 Limitations

- Particulate matter in mains reduces visibility, potentially to a level that no useful information can be obtained.
- The limited observations achievable may not be representative of the rest of the pipe.
- Maximum size of main that can be inspected is limited by the intensity of the available light source.
- Flow in charged mains can affect the controllability of the tool.

**Table F-28. Summary Fiberscope Inspection.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Water pipes and valves. |
| | Material type | Any. |
| | Service area | Potable. |
| | Access requirements | An entry point into the asset is required such as a fire hydrant or a tapping. |
| | Limitations relating to asset condition | No restrictions based on asset condition. |
| | Limitations relating to asset size/geometry | The minimum size main that can be inspected is approximately 2½ inches. Upper size limited by light source. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection can be undertaken on line or off line. |
| Technical suitability | Assessment parameters | Visual image of pipe internal surface analyzed manually for features such as sediment build up, corrosion products, etc. |
| | Integration with software tools | None. |
| | Commercialization of tool | Fiberscopes are widely available. |
| | Previous/existing use of the tool in sector | Tool not widely used. |
| | Accuracy/reliability | Qualitative/visual assessment of pipe surface or internal condition of valves. |
| | Ease of validation of results | Validation possible only by comparison with manual /direct observation. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Interpretation of results for consistent data requires training. Utility should have the competence to utilize the information provided by the tool operator. |
| | Technology required (level of tool sophistication) | Fiberscope and related accessories. |
| | Documentation | No Standards found or other. |
| | Availability of technical support | Technical support should be available from manufacturer. |
| Economic factors | Cost per inspection | Relatively low cost per inspection. |
| | Resource requirements | Requires team to operate camera and provide entry into pipeline. |

## F26.7 Bibliography

1. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A., *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
2. Randall-Smith, M., Russell, A. and Oliphant, R., *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992

## F27.0 Fracture Toughness (C-Ring) Testing

### F27.1 Overview

Fracture toughness testing gives an indication of the materials resistance to fracture failure. Many standards require PVC pipes to achieve a minimum "short term" fracture toughness value.

Fracture toughness testing is a destructive test where a specimen is statically loaded and the time to failure measured. It is generally used for quality control testing, but it could be applied to the testing of samples taken from in service PVC pipes. Fracture toughness can be measured on many materials, including steel and polystyrene. However, this review focuses on the fracture toughness testing of PVC used for pressure pipe.

### F27.2 Main Principles

C-ring fracture toughness testing allows the susceptibility of a PVC pipe to fracture failure to be determined. A section of (exhumed or new) pipe is marked with a line along the pipe axis. Several rings approximately $1^{3}/_{16}$ inches (30mm) in width are then cut from one end of the section.

The remaining length is subjected to the methylene chloride test (see Methylene Chloride Gelation Assessment review). If the results from this test are either type 1 or 2 then the ring is notched at the inside surface of the pipe parallel to the line drawn earlier. If however the test result is type 3, then the location of greatest attack is marked on all of the rings. The ring is then notched at the inside surface at this location.

A section is removed from the ring opposite to the notch to create a "C-ring". A static force is then applied, as shown in Figure F-4. The mass applied depends on the requirements of either a standard or the utility.

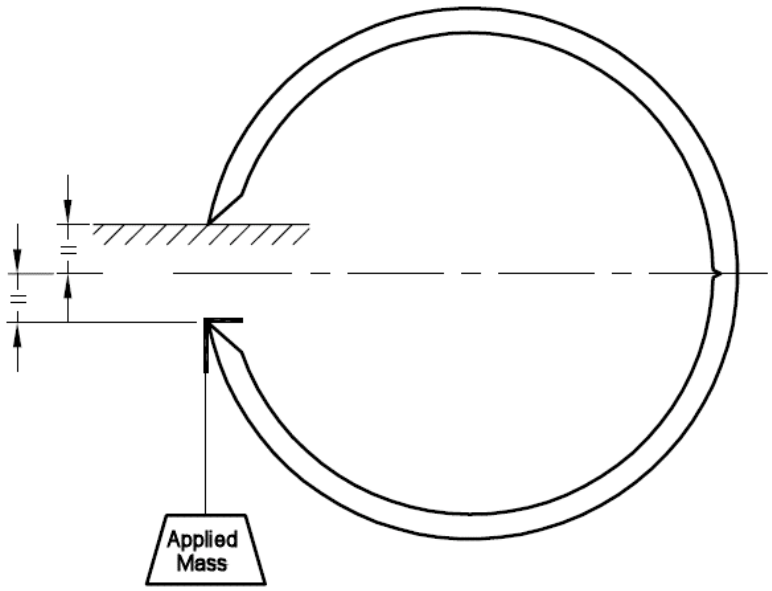


**Figure F-4. Schematic of C-Ring Fracture Toughness Testing.**

Testing can be conducted to either establish if the PVC pipe material meets a minimum 15 minute standard for which a single test is needed (although multiple tests are recommended), or multiple tests using a range of applied masses to establish fracture toughness behavior over time; including instantaneous fracture toughness via extrapolation. A typical requirement for PVC 15 minute fracture toughness is 4.5 MPa/m$^2$.

## F27.3 Application

C-ring fracture toughness testing is used to determine if a section of PVC pressure pipe exceeds a minimum fracture toughness set by the relevant standard or water utility (user).

- Standards which describe this test are as follows: ISO 11673, AS/NZS 1462.19:2006.

## F27.4 Practical considerations

- This test is widely used in the plastic pipe industry by both manufacturers and users. It should only be conducted in a laboratory by qualified personnel.
- If the notch is not located at the point of lowest gelation (point of greatest attack during methylene chloride testing), the test results cannot be considered reliable.

## F27.5 Advantages

- This test gives an indication of the pipe susceptibility to fracture failure.
- The test can be extended to obtain information about the probable lifetime of a pipe section.

## F27.6 Limitations

- The test is destructive and requires exhumation of pipe samples.
- The test is subject to variation, so a number of tests may need to be performed.
- The test must be conducted at the location of lowest gelation.
- The test only relates to the toughness properties of the material and not its susceptibility to failure due to point loading.

**Table F-29. Summary Fracture Toughness (C-Ring) Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes. |
| | Material type | uPVC or unplasticised poly(vinyl chloride). |
| | Service area | Potable and wastewater. |
| | Access requirements | Pipe sample test. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None on commonly used pipe sizes, specialized equipment may be required for testing of larger diameter pipes. |
| | Continuous/discrete | Discrete results. |
| | Destructive/non destructive | Destructive test. |
| | Interruption to supply/function | If pipe to be tested is in service it must be exhumed; supply will therefore be interrupted. |
| Technical suitability | Assessment parameters | Fracture toughness. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Test houses can supply testing capacity. |
| | Previous/existing use of the tool in sector | Tool is widely used by plastic pipe industry. |
| | Accuracy/reliability | Quantitative. Multiple measurements may need to be taken to ensure a reliable result. |
| | Ease of validation of results | Results can be validated by repeated testing. |
| Utility technical capacity | Asset management sophistication required | Generic testing procedure. |
| | Skills required (level of tool sophistication); usability | Operator should be suitably trained in the procedure. |

| | Criteria | Assessment |
|---|---|---|
| | Technology required (level of tool sophistication) | Test requires specialized notching tool. |
| | Documentation | ISO 11673, AS/NZS 1462.19:2006. |
| | Availability of technical support | Test can be conducted by test houses if required. |
| Economic factors | Cost per inspection | Low cost. Cost will vary depending on the time taken to complete testing. |
| | Resource requirements | Test requires a stable temperature environment and equipment to measure time to failure. |

# F28.0 Ground Penetrating Radar (GPR)

## F28.1 Overview

Ground Penetrating Radar (GPR) is a technique for acquiring subsurface information. GPR works by emitting short bursts of electromagnetic radiation into the ground and recording the radiation reflected to locate buried assets of any material.

The amplitude of each emitted pulse received by the GPR unit is recorded on a time scale (distance if wave velocity is known) giving a vertical plot for each pulse (called a trace). As the unit is moved along the ground, a series of traces are taken and colors or grey scale allocated to the amplitudes of each. The 'colored' traces are then placed along a distance scale and the 2D profile created (Ground Penetrating Radar, 2005).

The depth to which assets can be located is dependant on soil type and the size of the asset. The location of assets is achieved quickly in the field, though accurate interpretation of the results requires a skilled operator.

## F28.2 Main Principles

The GPR unit is moved across the ground surface to create a 2D profile of the area directly beneath its path. The profile can then be interpreted by the operator to identify features of importance. In order to locate buried assets, a series of profiles are taken, which can be used to find the boundaries of assets such as tanks, or their direction in the case of pipes. A series of profiles can also be used to create a 3D representation of an area.

GPR uses short bursts of VHF-UHF electromagnetic radiation, between 100 MHz and 1000 MHz, directed into the ground to acquire subsurface information. The actual frequency used varies but is a compromise between the depth of penetration and the accuracy required. By using longer wavelengths, increased penetration into soil can be achieved but there is a corresponding loss of resolution.

The depth of penetration is also dependant on soil type. Soils with low electrical conductivity provide the deepest penetration. In soils with high electrical conductivity, penetration is limited by the attenuation of the wave pulse by its conversion into thermal energy. Also, soils with large numbers of discontinuities will cause signal scattering, reducing the penetration of the pulse deeper into the subsurface.

The wave pulse emitted by the GPR is reflected from areas where there is an interface between two materials with different electrical properties, including objects, soil type interfaces and ground water (Ground Penetrating Radar, 2005). The depth at which these interfaces are located is calculated using the time it takes for the emitted pulse to travel into the ground, reflect and travel back to the receiver and the wave velocity. The velocity of the wave is dependant on the electrical permittivity or dielectric constant of the host material and a range of standard values is generally supplied with the GPR unit.

## F28.3 Application

GPR can be used to locate buried assets of any material type, but because of its cost, complexity, and limitations, GPR is usually the method of choice only for targets not locatable by other means, such as plastic or clay pipe.

- ASTM D6432-99 Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation

## F28.4 Practical considerations

- GPR units are available from a number of suppliers world wide. A trained operator is required to use the device effectively.
- The depth accuracy of GPR assessments is influenced by the knowledge of wave pulse velocity in the soil; where this is known, accuracy is quite high (usually within 10% of total depth). Where wave pulse velocity is unknown or estimated the accuracy can vary by a significant percentage of total depth. The horizontal accuracy is not affected by the wave pulse velocity, thus the surface location of the asset can be found within inches even though the depth may not be known with great accuracy.
- The repeatability of measurements is very high when there has been no change in soil conditions; variations in soil conditions will affect the results due to the change in the soil's wave pulse velocity and signal attenuation. Exact depth calculation is dependant on the quality of wave velocity information.
- The best results are achieved when the GPR unit is as close to the ground as possible, as any air gap will reduce the penetration and can induce interference at ground level.

## F28.5 Advantages

- GPR is quick and gives immediate results. Skilled operators can interpret data in the field or can it can be post processed.
- Unlike other location techniques GPR is able to locate polymer and clay assets.

## F28.6 Limitations

- Penetration into soils with high electrical conductivity, like mineralogical clays, can be limited to less than one meter (Ground Penetrating Radar, 2005).
- The ability to detect an asset below the water table is reduced by signal loss due to scattering at water table boundary and signal attenuation due to the high electrical conductivity below the water table.
- Uneven ground may require the unit to be raised off the ground, reducing the penetration depth and accuracy of the results.
- The equipment can be difficult to move on steep slopes.
- Skilled operators required for interpretation of data in the field.

**Table F-30. Summary Ground Penetrating Radar (GPR).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Environmental survey (buried assets). |
| | Material type | All materials. |
| | Service area | Potable and wastewater. |
| | Access requirements | GPR needs clear space at ground level, obstacles and very uneven ground can prevent use. |
| | Limitations relating to asset condition | No restrictions. |
| | Limitations relating to asset size/geometry | Assets of any size can be located. However small assets may be difficult to locate depending on their depth and the wavelength used. Rule of thumb is objects with a depth to size ratio of 12:1 to 24:1 are usually detectable with GPR, providing the signal can penetrate down to them before being attenuated. |
| | Continuous/discrete | Discrete. GPR uses sets of readings over a short distance gathered at a number of locations to locate assets. More advanced systems can use sets of images to create a 3D map of the subsurface. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection does not cause an interruption to supply. |
| Technical suitability | Assessment parameters | Location of buried assets. |
| | Integration with software tools | Depending on the model used, GPR equipment can be fed into computer programs to extract more data from the results obtained. |
| | Commercialization of tool | Equipment is available from a number commercial vendors. |
| | Previous/existing use of the tool in sector | GPR has been available for over 20 years, but has begun to be adopted by the utility locating industry only in the last 10 as more convenient, user friendly, and economical units have become available. |
| | Accuracy/reliability | Quantitative, though the accuracy of depth measurements is dependant on frequency and knowledge of soil properties and so can vary by several percent of depth. Claims on horizontal readings accuracy vary from inches to a foot. Ability to detect assets varies with material. |
| | Ease of validation of results | Results can be validated only through exposure of the asset. |
| Utility technical capacity | Asset management sophistication required | Generic. |
| | Skills required (level of tool sophistication); usability | Use of GPR requires a skilled operator to gather useful information. |
| | Technology required (level of tool sophistication) | Depending on the amount of data processing desired, computing can be done onsite by the unit or post processing can be done on to obtain more information including 3D plots. |
| | Documentation | ASTM D6432-99. |
| | Availability of technical support | Training courses are offered by the equipment manufacturers. |
| Economic factors | Cost per inspection | US$1,000 – $2,000 per day with a skilled operator. |
| | Resource requirements | GPR can be undertaken by a single person. |

## F28.7 Bibliography


1. Burn, L.S., Eiswirth, M., DeSilva D. and Davis P., *Condition Monitoring and its Role in Asset Planning*, Pipes Wagga Wagga 2001, Charles Sturt University, Wagga Wagga, N.S.W., 2001
2. Dingus, M., Haven, J. and Austin, R. *Nondestructive None Invasive Assessment of Underground Pipes*, AwwaRF, USA, 2002
3. Dolphin, L., *A brief background on ground penetrating radars*, http://www.ldolphin.org/GPRbkgnd.html , accessed 2005
4. Eiswirth, M., Burn, L.S. *New Methods for Defect Diagnosis of Water Pipelines*, 4th International Conference on Water Pipeline Systems, 28-30, York, UK, March 2001
5. *Ground Penetrating Radar*, http://fate.clu-in.org/gpr_main.asp , accessed 2005.
6. Trenchless technology Network *Underground Mapping, Pipeline Location Technology and Condition Assessment*, (downloaded from http://www.ttn.bham.ac.uk/Final%20Reports/Pipe%20Location%20and%20Assessment.pdf accessed 2006), 2002
7. ASTM D6432-99 Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation

## F29.0 Holiday Detector

### F29.1 Overview of Tool

This is a non-destructive method used to detect flaws such as pin holes, air bubbles, thin points and porosity in non-conductive (insulation type) coatings on conductive substrates and on concrete (for some detectors).

The substrate of the asset being inspected is connected to a current and a conductive brush is passed over the coating surface. Flaws are located when the brush moves over a flaw, which completes the electrical circuit.

Holiday detectors are also commonly known as porosity detectors, spark testers or jeepers.

### F29.2 Main Principles

Holiday detectors can be used on any asset which has a conductive substrate and non-conducting (insulating) coating, from DI pipes to tanks. Holiday detectors work by applying a constant current source to the coating substrate, which results in an applied test voltage. There are two main types of holiday detectors: 1) high voltage DC and 2) electric pulse units.

A typical DC detector delivers a stabilized DC output of up to 30kV with a resolution of 10V. Flaws are located by moving the detector over the coated surface; when the detector moves over a flaw, the applied potential 'jumps' from the substrate to the detector. A visual and/or audible alarm indicates when a fault is found. A range of accessories are available to be used with holiday detectors including:

- Internal pipeline disc and spiral wound brushes up to two meters diameter.
- External pipeline coil electrodes up to 1420 mm diameter.
- Flat brass wire brushes up to 600 mm long, fan brushes.

Pulse models can be used for determining porosity and location of pinholes in carbon impregnated coatings such as carbonated rubber, thick coatings such as rubber linings and on 'plastic'/fiberglass type coatings likely to become electrostatically charged. Models with 20kV and 40kV are designed for use in moist conditions and on wet or contaminated coating surfaces.

Some holiday detectors use the wet sponge method to detect pinholes in coatings. This method is recommended for thin film porosity testing (coatings under 150 μm), or in favor of high voltage testing, particularly when working with coatings in corrosive environments.

### F29.3 Application

Holiday detectors are useful for detection of flaws in coatings and wrappings on both flat and curved surfaces, such as pipes, tanks, valves and steel structures.

- Holiday detectors are required to comply with the requirements of AS3894.1-2002. They are also addressed in the National Association of Corrosion Engineers (NACE) Standards: TM0186-94; TM0384-94; RP0490-2001; RP0274-98 & RP0188-99

### F29.4 Practical Considerations

- Holiday detectors are handheld and come in a variety of types for the inspection of a wide range of asset types and can be obtained from a number of suppliers. They are

used widely in industries where the integrity of coating is important and can detect cracks, blow holes, burrs, air bubbles and inclusions (Figure F-5).

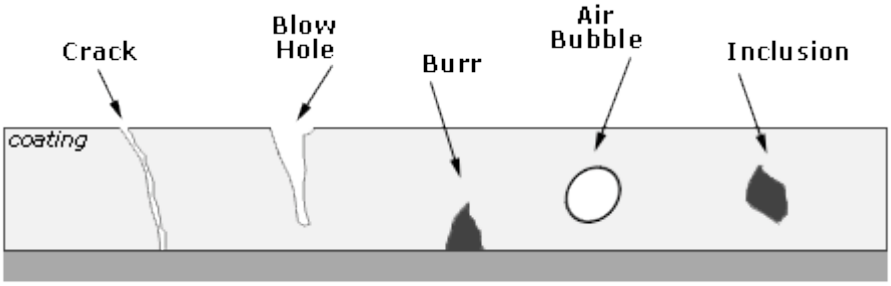


**Figure F-5. Defect Types Detectable by Holiday Testing (Reprinted with permission from: Buckleys, 2006).**

- A holiday detector should be used as soon as time and conditions permit after the coating has been applied and properly cured and, if possible, again prior to final project completion. When electrical inspection is conducted at the time of coating application, voids in the coating can be readily located and repaired, plus, it allows the applicator the opportunity to develop better coating application techniques.
- Electrical inspection prior to project completion is recommended as the protective coating may have been damaged during construction.
- Proper grounding of the holiday detector to the coated concrete substrate is essential in order to complete the electrical circuit of the holiday detector.
- Test voltage adjusted at the job site takes into consideration every aspect of the output circuit in relation to; ground resistance, structure resistance, coating thickness, capacitance losses, barometric pressure and electrode configuration.
- An alternative to setting test voltages in the field is to use the formula developed by the NACE and incorporated into several standards. The formula for the voltage to be applied to thin film coatings applied up to 30 mils (0.76 mm) thickness is $V = 525\sqrt{T}$, where T is the coating thickness in mils.
- Example: A coating 25 mils (0.64 mm) thick would work out to an inspection voltage of 2600V. For thicker applied coating the constant changes to 1250. Example: a coating 125 mils (3.175 mm) thick would work out to an inspection voltage of 14,000V.
- Care needs to be taken to not exceed the coating manufacturer's recommendations of test voltages. Manufacturers of the protective coating should always be consulted by the consumer with regards to dielectric strength of properly cured coatings and recommendations of maximum test voltages to be used on every formulated coating.
- It is not recommended that electric pulse (low voltage) detectors be used for the electrical testing of protective coating having a dry film thickness in excess of 0.51 mm.
- DC Pinhole/Holiday Detectors are far more efficient and accurate at finding pinholes, in coatings than AC spark testers.

## F29.5 Advantages

- Holiday detectors can be used to rapidly test the quality of a coating, including defects that cannot be detected by visual inspection.

## F29.6 Limitations

- Holiday detectors can only be used to find flaws in coatings whose substrate is made from a conductive material such as metal and concrete.
- Pulse type detectors are completely ineffective for inspection of prefabricated films such as PVC or polyethylene (PE) protective linings.

**Table F-31. Summary Holiday Detector.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Coated assets. |
| | Material type | Corrosion protection coatings on concrete and steel substrates. |
| | Service area | Potable and wastewater. |
| | Access requirements | Direct contact with coating. If external coating is buried then it must be exposed. Tool comprises of several components and is hand held. Sufficient room is required for an operator and electrical isolation area where an asset has been exposed for testing. |
| | Limitations relating to asset condition | No specific restriction related to asset condition. Testing cannot be conducted during rainfall. |
| | Limitations relating to asset size/geometry | No limitations relating to size of concrete element. |
| | Continuous/discrete | Continuous readings. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | The asset must be taken off-line if an internal coating is to be tested. |
| Technical suitability | Assessment parameters | Location of pin holes, air bubbles, thin points and porosity on non-conductive (insulation type) coatings. |
| | Integration with software tools | Compatible with an RS 232 data interface gives a printout of measured objects and can be transferred to PC with MS Hyperterminal. |
| | Commercialization of tool | Equipment is fully developed, readily available from commercial vendors and can be used off the shelf. |
| | Previous/existing use of the tool in sector | Widespread use internationally on bridges, road infrastructure in the petrochemical in the water industries. |
| | Accuracy/reliability | Accuracy is typically 2% at high resolution when calibrated on a known thickness location. |
| | Ease of validation of results | Certified high voltage DC and pulse crest meters can be used to verify the output voltage and the calibration of DC and crest holiday detectors respectively. |

| | Criteria | Assessment |
|---|---|---|
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | The technique does not require specialist knowledge. Requires minimal training. Operator will need to know be aware of safety procedures associated with the use of holiday detectors. |
| | Technology required (level of tool sophistication) | Apparatus digitally displays applied voltage, constant test current, and fully adjustable voltage and sensitivity controls. |
| | Documentation | AS3894.1-2002 and NACE Standards: TM0186-94; TM0384-94; RP0490-2001; RP0274-98 and RP0188-99. |
| | Availability of technical support | Technical support available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. Battery powered. |

## F29.7 Bibliography


1. Buckleys, *A Guide to Using DC Holiday Detectors* at http://www.buckleys.co.uk/holidayguide.htm, accessed 2006
2. Byerley, D. D. *Electrical Inspection of Protective Coatings Applied to Concrete Surfaces*, at http://www.tinker-rasor.com/tech/concrete.html
3. AS3894.1-2002 Site testing of protective coatings - Non-conductive coatings - Continuity testing - High voltage ('brush') method
4. NACE Standard Test Method TM0186-94. Holiday Detection of Internal Tubular Coatings of 250 to 760 µm (10 to 30 mils) Dry Film Thickness
5. NACE Standard Test Method TMO384-94. Holiday Detection of Internal Tubular Coatings of Less Than 250 µm (10 mils) Dry Film Thickness
6. NACE Standard Recommended Practice RP0490-2001 - Holiday Detection of Fusion-Bonded Epoxy External Pipeline Coatings of 250 to 760 um (10 to 30 mils
7. NACE Standard Recommended Practice RPO274-93. High Voltage Electrical Inspection of Pipeline Coatings Prior to Installation
8. NACE Standard Recommended Practice RP0188-99 Discontinuity (Holiday) Testing of New Protective Coatings on Conductive Substrates

# F30.0 Hydraulic Modeling

## F30.1 Overview

Many commercially available software packages are available that model the hydraulic behavior of pressure and gravity pipelines or networks. Hydraulic models are calibrated against measured values of pressure and/or flow. Calibration is further fine tuned by adjusting parameters like friction factors until the model reproduces the measured system response under a range of conditions.

Once calibrated, the hydraulic model can be used to identify hydraulic issues within the pipeline or network. When identified, asset inspection and other survey techniques can be used to investigate further.

## F30.2 Main Principles

Hydraulic models represent mathematically the relationships between flow parameters such as pressure, diameter, roughness and slope, and service demand. Hydraulic models are used at different stages of a pipe networks life which can include the following stages:

- Master planning – hydraulic models are used to predict the improvements and additions to the system which may necessary to accommodate future customers. In this situation models focus at a macro level with emphasis placed on larger transmission mains, pump stations and storage tanks.
- Preliminary design – hydraulic models are used to identify the facilities required to serve a particular area. In this situation modeling is usually focused to a limited portion of the network.
- Subdivision layout – hydraulic models determine the capacity requirements for the subdivision.
- Rehabilitation – hydraulic models are used to ensure that adequate capacity is maintained after rehabilitation of a pipeline. This is a very important consideration.

For stormwater and combined sewers, a verified model can be used to simulate network performance with respect to various performance indicators such as surcharge/flooding conditions. To do this, a verified model is run for storms of a range of intensities and durations to establish that each pipeline and overflow achieved the appropriate performance criteria (e.g., onset of surcharge).

## F30.3 Application

Hydraulic modeling is used for the analysis and design of pressure and gravity pipelines and networks.

- There are no Standards which require the use of hydraulic models.

## F30.4 Practical considerations

- Hydraulic models are widely used in the water industry so there are a large number of hydraulic modeling packages available, from both private vendors and public domains. Some are designed to undertake a specific hydraulic modeling task, while others are capable of a range of modeling processes.
- Most of the packages available enable network design, simulation and optimization. In addition many packages also incorporate water quality analysis and link to GIS.

- Costs of models vary dramatically, models such as EPANET (analysis only) and Netis are free, while other commercial packages are costly. However, the commercial packages come with more advanced features and better user interfaces than those freely available.
- Models require good data to be effective and collecting and assembling the data can be time consuming. In order to preserve their usefulness, the underlying input data must be maintained.
- Model calibration through adjustment of friction factors gives some indication of the pipe's internal condition. Where issues relating to service are predicted, asset inspection and other survey techniques can be used to investigate further.

## F30.5 Advantages

- Hydraulic models relieve engineers from tedious, iterative calculations and are able to take account of much more of the complexity of real world systems.
- Optimization tools/modules attached with the analysis module help in obtaining least cost solutions.
- They enable alternatives to be explored under a wide range of conditions resulting in more cost effective and robust interventions.

## F30.6 Limitations

- Hydraulic modeling software can be expensive to purchase for small companies and requires the training of staff to use the models.
- The majority of costs are mainly related to model development and the benefits are not realized until later in the form of quicker calculations and better decisions.
- Some packages have limitations on the number of network nodes they are able to handle, while others have limitations on their ability to link to a GIS system.

**Table F-32. Summary Hydraulic Modeling.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Water and wastewater networks. |
| | Granularity | System and sub-system level. |
| | Service area | Potable and wastewater. |
| Technical suitability | Focus of analysis | The relationships between flow, pressure, roughness, capacity and service. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good asset data is available, but simple models available for small authorities. |
| | Commercialization | Many commercial and public domain software models are available. |
| | Previous/existing use of the tool | Widely used worldwide. Majority of large authorities would have some form of modeling software. |
| | Ease of validation | Validation through data collection and comparison to network response. |
| | Flexibility wrt analysis (asset types) and granularity (system, asset level) | Designed for both network level modeling and sub network level modeling. Models are generally specific to water or wastewater service area (pressurized v open channel). |
| | Integration with other tools/GIS | Can link directly to GIS. |

| | Criteria | Assessment |
|---|---|---|
| Utility technical capacity | Asset management sophistication | Generic approach. |
| | In-house skills required | Asset manager/hydraulic engineer. |
| | Technology required | Computer based tool. Many systems link to GIS data. |
| | Documentation | Depends on software being used. Most come with detailed documentation. |
| | Data Requirements | Good quality asset data required, calibration data is necessary. |
| | Linking to asset data | Through asset IDs. |
| | Availability of software and technical support | Widely available through many vendors. Some models can be freely downloaded from the Internet. |
| | Usability | Depends on software. Most systems have an graphical user interface (GUI) that greatly improves the usability of the model. |
| Other | IT integration | PC based software. |
| | Tools costs (license and maintenance) | Varies depending on package. Some models are free, while some commercial packages are thousands of dollars. Many also have an annual license fee. |

## F30.7 Bibliography


1. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
2. *EPANET*, http://www.epa.gov/ORD/NRMRL/wswrd/epanet.html, accessed 2005
3. *SWMM*, http://www.epa.gov/ednnrmrl/models/swmm/index.htm, accessed 2005
4. Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A-S., and Erickson, M. *Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems*, EPA, EPA/600/R-02/029, 2002

# F31.0 Impact Echo Testing

## F31.1 Overview

The impact echo testing method is a non-destructive method primarily used for assessment of concrete assets. However, impact echo testing can also be performed on stone, plastic, masonry materials, wood and some ceramics. Application suitability depends on the properties and internal structure of the material being tested. Testing is conducted by impacting the asset surface, recording the signal reflected back to a transducer and analyzing that signal.

Impact echo tests are most often used to find the thickness of plate-like concrete elements from one side. Another major use is for locating and diagnosing internal flaws such as voids, honeycombing, delaminating, depth of surface opening cracks, and other damage in concrete.

If the member thickness is known, impact echo testing can also be performed to predict the strength of early age concrete. Impact echo testing can also be used to determine relative concrete quality for test cylinders and other samples with known thickness. This is achieved by measuring the concrete compression wave velocity.

## F31.2 Main Principles

Impact echo testing detects flaws in concrete based on reflection of compression waves from the bottom of the structural member or from any hidden discontinuity within the member. Concrete element thickness is determined by measuring waves that reflect off the backside of the concrete.

The waveform resulting from an impact to the asset is measured. The resulting time versus amplitude data includes energy from the initial impact as well as energy from echoes that have traveled through the concrete and echoed off of the back side or any discontinuity parallel to the test surface.

Impact echo testing apparatus consists of three main components:

- Impact source, often referred to as an impactor.
- Receiving transducer, often referred to as a displacement transducer.
- Waveform analyzer.

The selection of the impact source is important for successful impact echo testing. The size of the impactor is selected based on the depth and size of flaw that is to be detected. Steel spheres on spring rods are commonly used as the impact source.

The receiving transducer needs to be capable of accurately measuring surface displacement. A conically tipped transducer is often used in impact echo testing. Receiving transducers are secured in a special housing so that they can be used on vertical surfaces. A thin lead strip is used to provide acoustic coupling between the transducer and the test surface.

A waveform analyzer, or computer with high-speed digital data acquisition hardware, is used to capture the transient output of the displacement transducer, store the digitized waveforms, and perform signal analysis. The waveform analyzer needs to have a minimum high sampling frequency of 500 kHz. The receiving transducer should preferably be a broadband displacement transducer. Accelerometers have been used but they must not have resonant frequencies in the range of those measured during impact echo testing and additional signal processing is required.

Specialist software allows the data acquisition parameters to be set up and performs the data analysis.

## F31.3 Applications

The impact echo technique is most extensively used on flat areas but can also be used for tests on other geometries. Impact echo testing can be used, but is not limited to, the following asset types:

- Concrete slabs, pavements
- Concrete slabs consisting of two layers, including slabs with asphalt overlays
- Bond quality at internal interfaces
- Circular columns
- Square and rectangular beams and columns
- Walls
- Dams
- Hollow cylinders such as pipes and tunnels
- Post-tensioned structures for instance locating voids in grouted tendon ducts
- Depth of surface-opening cracks

In 1998, ASTM adopted a standard test method on using the Impact echo testing method to measure the thickness of concrete members:

- ASTM C 1383 'Standard Test Method for Measuring the P-wave Speed and Thickness of Concrete Plates Using the Impact echo testing Method'.

The standard test method involves two procedures. The first procedure determines the P-wave speed in the concrete by measuring the travel time between two surface receivers separated by a known distance. The second procedure measures the thickness using impact echo testing. The method is applicable to plate-like structures in which the smallest lateral dimension is at least six times the thickness of the member.

## F31.4 Practical Considerations

- The impact echo technique does not require specialist knowledge or training. Thickness measurements can be taken by unqualified staff. However experienced persons are required to check for flaws such as delamination.
- A telescoping pole can be used on flatwork or overhead.
- Generally impact echo testing instruments have built-in default concrete parameters. However for greater accuracy some instruments can be calibrated by testing at a point of known concrete thickness as a calibration reference.
- Impact echo testing equipment typically has a thickness range of 66mm up to 1.8m. The technology has the capability to be able to measure a minimum thickness of 38mm and a maximum thickness of 3.0m. However the ratio of width to thickness must be at least three. Accuracy is typically 2% at high resolution when calibrated on a known thickness location.
- If the thickness of the concrete being tested is not known, and two sides of the concrete element cannot be accessed, a second receiving transducer will need to be added in order to enable Spectral Analysis of Surface Wave (SASW) testing. This second

receiving transducer is often mounted on a detachable arm. In combination with the impact echo technique, SASW can be used for correlating strength vs. velocity in the field to laboratory tests of concrete specimens (cubes, beams or cylinders). SASW can also be combined with ultrasonic pulse velocity measurements for this purpose. The combination of impact echo thickness and internal flaw detection with SASW velocity measurement results in the most powerful and accurate way of determining the location and nature of defects.

- An underwater impact echo testing apparatus for point by point testing is also available.

## F31.5 Advantages

- Impact echo testing measures the thickness of concrete slabs and walls without the need for drilling, coring, or other destructive means.
- Only one side of the structure needs to be accessible for testing.
- The impact echo testing method can be used on existing coated structures. It works through paints, coatings and tiles.
- Additional analysis of the echo data allows multiple cracks and other complex internal flaws to be detected.

## F31.6 Limitations

- Impact echo testing is restricted in terms of the thickness and geometry of elements to be measured. The minimum thickness of concrete which can be tested is 38mm.
- Naumann and Haardt (2003) argue that there is a need for improved quantification of capabilities for measuring thickness, mapping or sizing layers of reinforcement, detecting and mapping of delaminations and cracks parallel to the surface for the impact echo method. This is especially the case where there is reinforcement congestion.

**Table F-33. Summary Impact Echo Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Concrete slabs, beams, columns, walls, pavements, tunnels, pipes, dams and other plate-like structures. |
| | Material type | Concrete, stone, plastic, masonry materials, wood and some ceramics. |
| | Service area | Potable and wastewater. |
| | Access requirements | Direct contact with asset. If asset is buried then it must be exposed, surface coatings do not need to be removed. |
| | Limitations relating to asset condition | No limitations relating to asset condition. |
| | Limitations relating to asset size/geometry | Some limitations relating to size/geometry: the minimum thickness of concrete which can be tested is 38mm and a maximum thickness of 3.0m. However the ratio of width to thickness must be at least three. |
| | Continuous/discrete | Discrete reading. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | The asset can remain in use and does not need to be taken off-line. |
| Technical | Assessment parameters | Thickness of concrete element, location and |

| | Criteria | Assessment |
|---|---|---|
| suitability | Assessment parameters | diagnosis of internal flaws, strength of early age concrete, and relative concrete quality. |
| | Integration with software tools | Can be integrated with software tools. |
| | Commercialization of tool | Equipment is available from selected commercial vendors. |
| | Previous/existing use of the tool in sector | Widespread use. |
| | Accuracy/reliability | Accuracy is typically + 2% at high resolution when calibrated on a known thickness location. |
| | Ease of validation of results | Results can be easily validated. For instance Spectral Analysis of Surface Wave testing (where a second receiving transducer is added when conducting echo impact testing) can be combined with ultrasonic pulse velocity measurements for determining concrete strength. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy to use by following simple procedure. Thickness measurements can be taken by unqualified staff. However experienced persons are required to check for flaws such as delaminations. |
| | Technology required (level of tool sophistication) | Apparatus comes in digital versions which calculate and display a graph concrete thickness along the member length. Thickness data table importable into popular spreadsheet programs. The data from up to 300 tests can be stored and downloaded. Some tools have a super thin concrete and surface wave analysis options built in. Velocity calibration at known thickness locations. |
| | Documentation | ASTM C 1383. |
| | Availability of technical support | Technical support available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. Battery powered. Resources required can also depend on asset being inspected. Buried assets need to be exposed. |

## F31.7 Bibliography


1. Naumann, J. and Haardt, P. *NDT Methods for the inspection of highway structures*. International Symposium (NDT-CE 2003). Non-Destructive Testing in Civil Engineering, pp2-5, 2003
2. ASTM C 1383 ‘Standard Test Method for Measuring the P-wave Speed and Thickness of Concrete Plates Using the Impact echo testing Method’

## F32.0 Indirect Tensile Strength Testing

### F32.1 Overview

The tensile strength of cylindrical cores (see Core/Coupon Sampling review) taken from concrete or asbestos cement pipes is used as a measure of the residual tensile strength of the pipe. Once extracted, the cores are compressed to failure. The compressive stress at failure can be used to indirectly obtain the residual tensile strength of the pipe from which the core was taken.

The testing of the cores is itself destructive. Since only cores are taken, the pipe itself must be repaired. If only one core is extracted, the pipe can be clamped. However, a common practice is to remove a section of pipe from which multiple cores are then taken. In this case, the pipe section must be replaced.

### F32.2 Main Principles

The tensile strength of a concrete or asbestos cement pipe reduces over time due to leaching of free lime; in a pipe where all the free lime has been leached, the residual tensile strength of the pipe will have been significantly reduced.

The tensile strength of the core can be used to determine the residual tensile strength of the pipe. A solid cylindrical core is cut from either a concrete or asbestos cement pipe section. The core is then subjected to a compressive load along its axis while the ends are constrained. By constraining the ends, the stress state in the core can be resolved in 2D allowing the residual tensile strength of the core to be calculated. The core is tested to failure.

By measuring the current tensile strength of the core and comparing that to values for virgin pipe, the rate of deterioration of the cement matrix can be estimated and applied to predict the time to failure of the pipe under known operating and installation conditions.

The phenolphthalein and carbonation tests can be used prior to this test to give an indication of the depth of free lime depletion through the pipe wall (see Phenolphthalein Indicator review).

### F32.3 Application

Indirect tensile strength testing is a method for obtaining the residual tensile strength of cementituous pipes in water and wastewater networks. The test procedure for this tool is based on the following standard;

- AS 1012.10 – 2000 “Determination of indirect tensile strength of concrete cylinders (‘Brazil’ or split test) and ASTM C-496-96 “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens”

### F32.4 Practical considerations

- This is a new test method and had yet to be adopted widely by industry.

### F32.5 Advantages

- Tool can be used to predict the remaining life of a cementituous pipe asset.

### F32.6 Limitations

- This is a new test that is not widely used. The pipe must be exhumed for removal of test sample, and the pipe repaired or pipe section replaced.

- Testing of asbestos cement pipe samples is subject to health and safety considerations.

**Table F-34. Summary Indirect Tensile Strength Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipe. |
| | Material type | Asbestos cement, concrete. |
| | Service area | Potable and wastewater. |
| | Access requirements | Need access to pipe surface to remove core sample. |
| | Limitations relating to asset condition | No restrictions due to asset condition, pipe lining /coatings need to be removed prior to testing. |
| | Limitations relating to asset size/geometry | No restriction. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Destructive. |
| | Interruption to supply/function | Pipe must be taken off-line to extract core sample. |
| Technical suitability | Assessment parameters | Tensile strength. |
| | Integration with software tools | None. |
| | Commercialization of tool | Technique is new and only provided by specialized consulting groups. |
| | Previous/existing use of the tool in sector | Limited; utilized in condition assessment of several AC wastewater pressure mains. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Service is provided by specialized consulting groups. |
| | Technology required (level of tool sophistication) | Low tech. |
| | Documentation | AS 1012.10 – 2000 and ASTM C-496-96. |
| | Availability of technical support | Service is provided by specialized consulting groups. |
| Economic factors | Cost per inspection | Depends on level of analysis required. |
| | Resource requirements | Personnel and equipment required to remove cores. Test and lab equipment. |

## F32.7 Bibliography


1. Davis, P., De Silva, D., Gould, S. & Burn, L.S. *Condition assessment and failure prediction for asbestos cement sewer mains*, presented to Pipes Wagga Wagga 2005 Conf., Charles Sturt University, Wagga Wagga, NSW, Australia, 17–20 October, 2005
2. AS 1012.10 – 2000 "Determination of indirect tensile strength of concrete cylinders ('Brazil' or split test)
3. ASTM C-496-96 "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens"

# F33.0 Infiltration and Inflow – Sewer Flow Survey

## F33.1 Overview

Sewers flow surveys are often used to calibrate hydraulic models (see Hydraulic Modeling review), but they can also be used to determine where infiltration of groundwater or inflow of water (other than infiltrated groundwater such as rain water) into the system is a problem. Specialized flow surveys can be used to locate the areas of the system where the flows originate and estimate their magnitude.

The aim of a flow survey is to obtain actual flows in the sewer system during both dry and wet weather conditions. A calibrated hydraulic model can also be used to analyze scenarios for reducing infiltration through various interventions.

## F33.2 Main Principles

Infiltration and inflow (I&I) are important because water from these extraneous sources reduces the available capacity of sewer systems and capability of treatment facilities to treat waste waters. Infiltration occurs when existing sewer lines are poorly designed and constructed, or undergoes material and joint deterioration allowing groundwater to enter. Inflow may occur when rainfall enters the sewer system through direct connections such as drains, sump pumps, manhole covers and indirect connections with storm sewers.

Flow surveys can be used to identify parts of the system where I&I flows originate and estimate their magnitude. To do this, the utility must first identify if the sewerage system has problems through review and analysis of existing flow records such as treatment plant influent data, pump run time data, overflow locations and estimated amounts, customer complaints, etc.

The system is then divided into subsystems and the key manholes located at the outlet of each subsystem. Flows to these key manholes are monitored and compared to the expected sewer flows from the subsystems.

Once the problem subsystems are identified, physical inspection, rainfall data, and rainfall simulation are used to further define the I&I problem. Smoke testing, visual and CCTV inspections (see Smoke Testing, Visual Inspection and CCTV Visual Inspection reviews respectively) can then be undertaken to provide to identify and prioritize the repair and/or rehabilitation if an intervention is deemed appropriate.

## F33.3 Application

I&I sewer flow surveys are used to obtain a better understanding of I&I issues in wastewater networks. There are no Standards which require the use of I&I flow surveys

## F33.4 Practical considerations

- Flow surveys have a wide application in the water sector and can be undertaken either in-house or through specialist contractors/consultants.
- Groundwater maps can be constructed for high, medium and low water levels and overlaid with asset depth data to help isolate areas of interest.
- Flow meters should be selected that record both the depth and velocity of flow. Once data is collected it should be analyzed to give several flow parameters including average dry-day flow, maximum and minimum diurnal flow, inflow, rainfall-induced infiltration, seasonal infiltration, etc.
- A calibrated hydraulic model can also be used to analyze scenarios for reducing I&I through various interventions strategies.

## F33.5 Advantages

- I&I flow surveys allow the detection of excessive flows and the targeting of capital investment to solve operational issues in sewer networks and treatment plants.
- Identification of I&I problems can allow for rehabilitation and/or replacement to reduce the stress of pipe systems and treatment plants.

## F33.6 Limitations

- Identification of the problem through flow surveys and analysis does not necessarily lead to solutions.
- Reduction in I&I though capital investment in sewerage infrastructure has a variable impact.
- Other interventions and drivers need to be considered in conjunction with the results of I&I studies.

**Table F-35. Summary Infiltration and Inflow – Sewer Flow Survey.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Wastewater networks. |
| | Granularity | Spatially drainage area and below. |
| | Service area | Wastewater |
| Technical suitability | Focus of analysis | I&I. |
| | Scalability of tool/approach | Scaleable; survey approach can be used for any size company. |
| | Commercialization | Framework approach; commercial survey services could be contracted. |
| | Previous/existing use of the tool | Wide application. |
| | Ease of validation | Validity depends on the quality of hydraulic models and, in turn, the quality of flow and other data; independent validation difficult. |
| | Flexibility with respect to analysis (asset types) and granularity (system, asset level) | Wastewater; asset to sub-system level. |
| | Integration with other tools/GIS | Flow data could be analyzed in GIS framework as well as hydraulic models. |
| Utility technical capacity | Asset management sophistication | Generic approach. |
| | In-house skills required | Professional engineering skills required. |
| | Technology required | PC based analysis; modern flowmeters. |
| | Documentation | A range of papers written on approach. |
| | Data Requirements | High; data is needed to identify areas. |
| | Linking to asset data | N/A |
| | Availability of software and technical support | N/A |
| | Usability | N/A |

## F33.7 Bibliography


1. Vass, R. Pugh, A, *Inflow and Infiltration Study*, Ozwater 2003, Proceedings AWA 20th Convention, Perth, April 2003
2. Ellis, J. B *Sewer inflitration/exfiltration and interactions with sewer flows and groundwater quality*. 2nd International Conference Interactions between sewers, treatment plants and receiving waters in urban areas – Interurba II 19-22 Feb. 2001, Lisbon, Portugal, 311-319, 2001
3. Joannis, C., Commaille, J-F and Dupasquier, B. *Assessing infiltration flow-rates into sewers*, Proceedings 9th ICUD, Global Solutions for Urban Drainage, Portland, USA, 2003
4. Berthier, E., Andrieu, H, Fasquel, M and Creutin, J-D. Generation of flows in urban *stormwater drainage systems: The role of soil*, 2001 http://www.lcpc.fr/en/sources/blpc/pdf/bl231-079-en.pdf

## F34.0 In-Pipe Acoustic Inspection Tools (Sonar)

### F34.1 Overview

CCTV inspection is the industry standard technology for measuring the internal condition of sewers and stormwater pipes. However, this technique is limited in that it only allows inspection above the flow line – interpretable CCTV images can not be obtained below the flow line due to the turbidity of sewage (see CCTV Visual Inspection review).

An alternative technique, sonar, also provides pictorial evidence of sewer condition. Unlike CCTV, sonar can be used in full sewers, or to inspect the sewer beneath the flow line. Sonar can also be used to give an image of the sewer above the flow line. However, different transducers and electronics are required for operation in air and water. As such, sonar suitable for below the flow line can not give an image of the sewer above the flow and vice versa.

During the survey, a sonar head is introduced into the sewer on a suitable module (a tractor, crawler, float, etc.). The head transmits ultrasonic signals that are reflected from the surface of the sewer; the reflected signals are detected by the head. The time delay associated with the reflected signal is used to generate a profile of the pipe surface.

Sonar can generate a real time 360-degree outline of the interior of a full pipe, or the outline of the wetted area in a partially full pipe (or the non-wetted area for air sonar).

In the case of a partially full pipe, sonar can be used in conjunction with CCTV to allow inspection of the entire sewer, with sonar being used to provide information about the sewer condition below the flow line.

Sonar inspection has been utilized mainly in sewer pipelines. In water mains, the resolution of the inspection technique is not sufficient to detect small defects that are significant in pressure applications. Furthermore, other competing inspection technologies (including leakage detection) can provide the required information. Nevertheless, the principle of sonar inspection can still be used to measure the distance to the pipe wall.

Acoustic systems for flaw detection are also available that are based on detecting vibrations and other phenomena caused by the spreading of mechanical sound waves, and are suitable for detecting cracks and for determining the state of connections and pipe bedding.

### F34.2 Main Principles

Sonar technology involves the emission of an acoustic pulse from a transducer and the subsequent detection of the pulse echo reflected from a surface. The time between the transmission and reception of the acoustic signal can be used to determine the distance from the transducer to the surface that reflected the pulse.

Sonic pulses are reflected from any acoustic impedance boundary. The greater the difference in the impedance of two materials, the more sonic energy is reflected. The impedance mismatch between water and the wall of a pipe, between air and the pipe wall, or the interface between air and water are all excellent sonic reflectors.

In the case of sewer inspection, the sonar transducer is mounted in an appropriate housing and towed (or propelled) through the sewer. An acoustic signal is transmitted radially toward the sewer wall using a rotating transducer. By analyzing the received echo, the distance from the transducer to the wall can be calculated.

As the inspection progresses, the signal is analyzed to generate images of the sewer's interior perimeter in real time. The profile is displayed on a monitor and allows features such

as the pipe wall, displaced bricks and silt/growths to be identified. Results can be recorded on video or digitally.

When used in conjunction with CCTV equipment, the sonar tool is suspended in the sewage below the rig. CCTV images are taken of the sewer above the flow line, and sonar allows inspection below the flow line.

In some applications (for example, inspection of furnace tubes), this technology is used to give a measure of both the internal pipe geometry and the thickness of the wall. Thickness measurement is achieved because, on arrival at the tubing wall a portion of the sound pulse energy reflects back towards the transducer, while a fraction of the energy propagates into the steel tube wall. At the outer tube surface a similar reflection occurs, sending energy back in the direction of the inner wall and transducer.

On-board digital signal processing of the returned echoes determines the 'time of flight' in the tubing wall. The time between the transmission and reception of the acoustic signals are then used to compute the tubing wall thickness and radial measurement based on the known acoustic propagation properties of the tubing material.

## F34.3 Application

The primary use for sonar equipment is to inspect and assess the structural condition of otherwise inaccessible or flooded sections of large diameter sewers. The technology is applied to inspection of pipes in the process industry and could be adopted for inspection of water mains, though competing technologies are available for this application.

Acoustic systems based on detecting vibrations and other phenomena caused by mechanical sound waves, are suitable for detecting cracks as well as for determining the state of connections and pipe bedding.

## F34.4 Practical considerations

- Sonar inspection is a commercially developed technology, which provides a practical alternative to CCTV in large diameter or surcharged mains.
- The precision of sonar inspection is a function of several factors including the speed of movement through the sewer, the quantity of suspended solids in the sewage, and the degree of turbulence:
  - Under ideal operating conditions using slow forward advancement, sonar could indicate small openings or cracks, around 5 mm wide. Under normal operating conditions, however, very small defects may not be seen. The sonar image will, however, identify those defects clearly requiring action.
  - Heavy suspended solids and debris in the sewage can block the sonar signal.
  - Incoming flow from connections causes air entrainment in the main sewer downstream of the connection. The entrained air bubbles tend to block the sonar signal, and as a result interference may be seen in the image.
- When combined with CCTV, sonar allows an inspection of the entire sewer, with sonar providing the images below the flow line. A large number of combined sonar and CCTV surveys have been undertaken in North America.
- The ultrasonic calliper and the rotating sonic calliper rotator (RPC) are examples of commercially available tools. The RPC has been used to inspect plastic, concrete, brick and clay pipes. It can be operated in pipes as small as 0.5 m or as large as 4 m. The RPC cannot operate in both air and water simultaneously, because different electronics

and transducers are needed. It records only the part of the pipe that is above water, or the part that is below water level.

- Studies in the United States showed that air sonar used for measurement above the flow line was not sufficiently accurate over the larger distances involved in 3.6 m diameter pipes to allow valid condition assessment.

## F34.5 Advantages

- Sonar provides a convenient way to measure the cross-sectional area of a sewer.
- Sonar can be used to inspect and assess the structural condition of otherwise inaccessible or flooded sections of large diameter sewers.
- Sonar allows inspection of the portion of the sewer below the flow line. When combined with CCTV, sonar allows an inspection of the entire sewer, with sonar providing images below the flow line.

## F34.6 Limitations

- The technique requires specially trained personal to undertake the inspection and interpret the results.
- Sonar can not be operated in air and water simultaneously, as different transducers and electronics are required.
- Sonar is a more specialized service than CCTV, with less service providers.

**Table 3-36. Summary In-Pipe Acoustic Inspection Tools (Sonar).**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Pipes. |
| | Material type | Any. |
| | Service area | Potable and wastewater. |
| | Access requirements | Access to sewer interior is required. |
| | Limitations relating to asset condition | Sewer must be passable. |
| | Limitations relating to asset size/geometry | Limited to large diameter pipes. |
| | Continuous/discrete | Continuous. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection can be undertaken on-line. |
| Technical suitability | Assessment parameters | Sewer defects and geometry. |
| | Integration with software tools | Software used to process signals. |
| | Commercialization of tool | Fully commercialized. |
| | Previous/existing use of the tool in sector | Wide use, especially in conjunction with CCTV. |
| | Accuracy/reliability | Semi-quantitative indication of defects. |
| | Ease of validation of results | Validation through direct observation required. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Highly skilled. |
| | Technology required (level of tool sophistication) | Highly technical. |
| | Documentation | Service likely to be provided by third party. |
| | Availability of technical support | Service likely to be provided by third party. |
| Economic factors | Cost per inspection | Varies depending on pipe size, accessibility and purpose of survey. |
| | Resource requirements | Requires team to operate equipment and provide entry into pipeline. |

## F34.7 Bibliography


1. ASCE, Sanitary Sewer Overflow Solutions, American Society of Civil Engineers, EPA Cooperative Agreement CP-828955-01-0, April 2004
2. McDonald, S.E.; Zhao, J.Q. Condition assessment and rehabilitation of large sewers, National Research Council of Canada, Institute for Research in Construction, NRCC-44696, 2001 (downloaded from www.nrc.ca/irc/ircpubs)
3. Ratliff, A., An overview of current and developing technologies for pipe condition assessment, ASCE 2004
4. Zhao, J. Q. Trunk Sewers in Canada, APWA International Public Works Congress NRCC/CPWA Seminar Series "Innovations in Urban Infrastructure," 1998

# F35.0 In-Pipe Hydrophones

## F35.1 Overview

Water loss control programs are widely used throughout the water industry and a major phase of these programs is leak detection. Leak detection is used to determine the exact location of a leak. Repair of the leak saves revenue and conserves water and energy.

To locate a leak precisely, a hydrophone can be inserted directly into a pipe. Leaks are identified by the noise they create. Once a leak is identified, it can be located by moving the hydrophone to the position where the noise is clearest, then determining the location of the hydrophone at this point.

## F35.2 Main Principles

Hydrophones are used to detect leaks due to the noise created as the water is forced out under pressure through the pipe wall. Leaks generally make three sounds, a medium frequency sound, 500-800 Hz, associated with the water passing through the orifice/leak, and two low frequency noises, 20-300 Hz, associated with the water stream impacting the soil and circulating outside of the pipe (Burn et al, 1999). The sound of the leak is also able to give an indication of leak magnitude.

Hydrophones are generally tethered systems, although some free swimming technologies are also available. In either case, an underwater microphone is inserted into a pipe and moves along the pipe with the flow. The hydrophone is introduced to the pipe via a valve and tapping made for the purpose of the inspection. There is also potential to utilize existing access points provided by hydrants or fittings.

## F35.3 Application

Hydrophones are used for the detection of leaks in water distribution and transmission pipelines. Research has also been undertaken into the use of the technology for pressurized sewers (force mains).

- There are no a standards for In-Pipe Hydrophone use.

## F35.4 Practical considerations

- A tethered system offers the least risk of inspection systems getting stuck, zero or minimal supply disruption, and requires a single access point for entry and recovery of the hydrophone.
- A new system is also available where the hydrophone and recording equipment is encapsulated into a single unit that is inserted into the main without a tether and collected down stream. The recorded data can then be downloaded and analyzed.
- Non-tethered or free-flying systems have the potential to cover much greater range of the pipe network during each use; however there is a risk of losing the tool. Tethered hydrophones can become fouled in valves and have limited range, and require a minimum flow rate to pull them along the main.
- For tethered systems, when a leak is detected the hydrophone can be moved back along the pipeline in order to pinpoint the leak.
- Currently, the most widely used commercial system is Sahara$^{TM}$. This tool has been in operation within North America since 2004. It was developed by the Water Research Centre (WRc) in the United Kingdom.

## F35.5 Advantages

- As an in-pipe technique, factors like pipe material and diameter do not influence the detection of leaks, as they do in on-pipe techniques (see Leakage Detection).
- Tethered hydrophone technology can be used to accurately pinpoint leaks.
- Non-tethered systems can survey a large length of pipe than tethered systems in each use.

## F35.6 Limitations

- The Sahara technology is relatively expensive, so other techniques and equipment should be used to target and prioritize area to identify where it would be most useful.
- Tethered hydrophones can become fouled in valves and have limited range, and require a minimum flow rate to pull them along the main.
- There is a risk of losing free swimming hydrophones.

**Table F-37. Summary In-Pipe Hydrophones.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipelines. |
| | Material type | Any. |
| | Service area | Potable. |
| | Access requirements | Hydrophones need special assemblies to allow entrance into main. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | Restricted to large diameter mains. |
| | Continuous/discrete | Continuous. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection be undertaken on-line. |
| Technical suitability | Assessment parameters | Presence and location of leaks. |
| | Integration with software tools | Software used to analyze data. |
| | Commercialization of tool | Fully commercialized service. |
| | Previous/existing use of the tool in sector | Used in the United States since 2004. |
| | Accuracy/reliability | Quantitative assessment of location, semi-quantitative assessment of leak size. |
| | Ease of validation of results | Only through excavation at leak site. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Specialist service. |
| | Technology required (level of tool sophistication) | Sophisticated tool. |
| | Documentation | Use reported in the technical and trade literature. |
| | Availability of technical support | Via specialist service providers. |
| Economic factors | Cost per inspection | Relatively expensive. |
| | Resource requirements | Team to undertake survey and patented equipment. |

## F35.7 Bibliography

1. Chastain-Howley, *A Transmission Main Leakage: How to reduce the risk of a catastrophic failure*, Leakage 2005 - Conference Proceedings, 2005

2. Sahara homepage, http://www.wrcplc.co.uk/sahara/, accessed 2006

# F36.0 Insulation Test

## F36.1 Overview

Overtime the performance of the insulation in an electrical circuit may deteriorate with exposure to heat, moisture, vibration or corrosive materials. Deteriorated insulation allows a steady flow of electricity to escape from the electrical circuit during operation. This can lead to equipment failure. Potentially dangerous voltages can become present if protective measures are inadequate.

The procedure for determining equipment insulation resistance is widely used and readily understood by trained electrical technicians, can be easily undertaken by using a hand held testing device and is a non-destructive assessment technique.

## F36.2 Main Principles

As part of an electrical and conditioning monitoring program, electrical insulation testing is commonly undertaken to determine the insulation resistance of electrical circuits, since the efficiency and running costs of equipment are increased when electrical circuits exhibit poor insulation properties.

In order to assess an electrical circuit for its electrical insulation performance, a hand held megaohmmeter is used to test the insulation resistance by applying a known voltage (500V or 1000V DC for low voltage systems) to the circuit being assessed and measuring the current flow to ground. From this measurement the resistance of the equipment insulation can be determined, with a result exhibiting a low resistance between phases or phase to earth indicating that insulation breakdown may be occurring, or moisture ingress and/or partial short circuits may be present. The DC test voltage is applicable to both AC and DC circuits.

## F36.3 Application

Electrical insulation testing is a commonly used and recognized technique for assessing electrical circuits and equipment insulation performance in motor windings, cables, switchboards and motor control centers.

- Insulation testing is referred to in AS/NZS 3000-2000.

## F36.4 Practical Considerations

- Insulation testing to determine the condition of electrical equipment and circuits should be undertaken by trained electrical technicians and engineers, since knowledge and experience of electrical circuits and interpretation of the readings obtained from the analysis is required.

## F36.5 Advantages

- Insulation testing is common practice, inexpensive and easy to use.

## F36.6 Limitations

- When determining the insulation resistance, the piece of equipment or circuit is required to be isolated prior to assessment and as a result can not be undertaken as an on-line assessment technique.
- When assessing electrical motors, minor faults may not be identified and sensitive equipment must be disconnected to avoid possible damage.

**Table F-38. Summary Insulation Test.**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Motor winding, cables, switchboards, motor control centers. |
| | Material type | Electrical insulation. |
| | Service area | Potable and wastewater. |
| | Access requirements | Access to conductor and insulation. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discreet readings. |
| | Destructive/non destructive | Non-destructive (providing electronic components isolated). |
| | Interruption to supply/function | None. |
| Technical suitability | Assessment parameters | Insulation strength. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Fully developed and off the shelf. |
| | Previous/existing use of the tool in sector | Standard sector practice. |
| | Accuracy/reliability | Good accuracy. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Electrician will already be trained to use. |
| | Technology required (level of tool sophistication) | None. |
| | Documentation | Well documented. Electric motor. |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | Low cost per inspection |
| | Resource requirements | One man no more than half an hour per motor (allows for disconnection/reconnection). |

## F36.7 Bibliography

1. AS NZS 3000-2000 Electrical Installations (known as wiring rules)

# F37.0 Intelligent Pigs

## F37.1 Overview

Intelligent pigs use different technologies to locate defects or gather other information about large diameter pipelines. Several non-destructive inspection technologies can be integrated into these tools:

- The ***Magnetic Flux Leakage technique***, used to detect corrosion or thin walls.
- ***Ultrasonic sensors***, used to detect coating delamination, cracks, dents and gouges.
- ***Global Positioning System*** (GPS) technology is being adapted to obtain the exact location of any problem in the pipe or to map the pipe itself.
- ***Geometry tools***, which use mechanical arms or electro-mechanical means to measure the bore of pipe. In doing so, the tool identifies dents, deformations, and ovality. It can also sense changes in girth welds and wall thickness. In some cases, these tools can also detect bends in pipelines.

## F37.2 Main Principles

A pig is a device inserted into a pipeline that travels freely driven by the flowing media to do a specific task within the pipe, such as cleaning. An intelligent pig carries complex monitoring technologies that provide information on the condition of the pipe and/or its contents. With a few exceptions, intelligent pigs simply gather data, which is then analyzed by engineers to determine and report on the condition of the pipe.

Intelligent pigs are inserted into the pipeline at a location that has a special configuration of pipes and valves where the tool can be loaded into a receiver. The receiver can then be closed, sealed, and the flow of the pipeline product directed to launch the tool into the main line of the pipeline.

A similar setup is located downstream, where the tool is directed out of the main line into a receiver. The tool is then removed and the recorded data retrieved for analysis and reporting.

The two most common requirements are for tools that can undertake geometry/diameter measurement and detect metal-loss/corrosion. However, the information that can be provided by these tools covers a much wider range of inspection and troubleshooting needs, including:

- Diameter/geometry measurements
- Curvature monitoring
- Pipeline profile
- Temperature/pressure recording
- Bend measurement
- Metal-loss/corrosion detection
- Photographic inspection
- Crack detection
- Wax deposition measurement
- Leak detection
- Product sampling
- Mapping

Three common technologies incorporated into smart pigs are described further below.

***Geometry Tools:*** Geometry tools use mechanical arms or electro-mechanical means to measure the bore of pipe. In doing so, the tool identifies dents, deformations, and other variation is cross-section. It can also sense changes in girth welds and wall thickness. In some cases, these tools can also detect bends in pipelines.

***Ultrasonic Tools:*** There are two types of tools commonly used for inspections of hazardous liquid pipelines based on ultrasonic measurements.

- Compression Wave Ultrasonic Testing (UT) tools measure pipe wall thickness and metal loss. The first commercial application of UT technology used compression waves. These tools are equipped with transducers that emit ultrasonic signals perpendicular to the surface of the pipe. An echo is received from both the internal and external surfaces of the pipe and, by timing these return signals and comparing them to the speed of ultrasound in pipe steel, the wall thickness can be determined.
- Shear Wave Ultrasonic Testing (also known as Circumferential Ultrasonic Testing, or C-UT) is the non-destructive examination technique that most reliably detects longitudinal cracks, longitudinal weld defects, and crack-like defects (such as stress corrosion cracking). Because most crack-like defects are perpendicular to the main stress component (i.e., the hoop stress), UT pulses are injected in a circumferential direction to obtain maximum acoustic response.

***Magnetic Flux Tools:*** There are two types of tools commonly used for inspections of pipelines based on magnetic flux measurements (for more information see Magnetic Flux Leakage review).

- Magnetic Flux Leakage (MFL) tool: an electronic tool that identifies and measures metal loss (corrosion, gouges, etc.) through the use of a temporarily applied magnetic field. As it passes through the pipe, this tool induces a magnetic flux into the pipe wall between the north and south magnetic poles of onboard magnets. A homogeneous steel wall – one without defects – creates a homogeneous distribution of magnetic flux. Anomalies (i.e. metal loss (or gain) associated with the steel wall) result in a change in distribution of the magnetic flux, which, in a magnetically saturated pipe wall, leaks out of the pipe wall. Sensors onboard the tool detect and measure the amount and distribution of the flux leakage. The flux leakage signals are processed, and resulting data is stored onboard the MFL tool for later analysis and reporting.
- A Transverse MFL/Transverse Flux Inspection tool (TFI) identifies and measures metal loss through the use of a temporarily-applied magnetic field that is oriented circumferentially, wrapping completely around the circumference of the pipe. It uses the same principal as other MFL tools except that the orientation of the magnetic field is different (rotated 90°). The TFI tool is used to determine the location and extent of longitudinally-oriented corrosion. This makes TFI useful for detecting seam-related corrosion. Cracks and other defects can be detected also, though not with the same level of reliability. A TFI tool may be able to detect axial pipe wall defects – such as cracks, lack of fusion in the longitudinal weld seam, and stress corrosion cracking – that are not detectable with conventional MFL and ultrasonic tools.

## F37.3 Application

Intelligent pig technology is generally used for inspection of large diameter steel pipeline assets in the oil and gas sector.

These tools only have limited applicability to the water/wastewater industry, although some critical steel mains may be candidates for intelligent pig technology.

## F37.4 Practical considerations

- In selecting the tools most suitable for in-line inspections, pipeline operators must know the type, thickness and material of the pipe being measured; the types of defects that the pipe might be subject to (e.g. internal corrosion, external corrosion, weld cracks, stress corrosion cracks); and the risk presented by the pipe section being measured.
- Intelligent pigs are expensive devices that require specialized insertion and retrieval arrangements. These are commonly designed into oil and gas pipelines, but are not incorporated into the design of water transmission mains.
- Intelligent pigs are commercialized and widely used in the oil and gas sector. It is unlikely that there will be widespread use of pigging in the water sector because of the high capital cost of pig launch/recovery equipment, discoloration problems caused by abrasion as the pig passes along the line, and the obstructions in many transmission pipes due to corrosion, valve construction, and changes in size.
- Pigging would also require the main to be taken out of service for some hours.
- Some of the new pigs are able to alter size to allow them to be used for multi-diameter pipes (Willke, 1998).

## F37.5 Advantages

- High resolution intelligent pigs can accurately detect, size, and locate corrosion or any other anomalies in pipelines. Once the problem is detected the information can be used to develop a pipeline de-rating schedule, implement a repair or replacement program, determine if re-inspection is necessary, and evaluate effectiveness of a corrosion inhibitor program (Jones et al, 1995).

## F37.6 Limitations

- Intelligent pigs are expensive devices that need specialized insertion and retrieval structures. Traditionally they have been used in the gas and oil industry and will only have only limited applicability to the water/wastewater industry.

**Table F-39. Summary Intelligent PIGS.**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Pipelines. |
| | Material type | Large diameter pipes of rigid material; more suited to welded steel. |
| | Service Area | Potable. |
| | Access requirements | Require specialized insertion point (pig traps) to avoid interruption to flow. |
| | Limitations relating to asset condition | Asset needs to be in relatively good condition to avoid the pig getting stuck. |
| | Limitations relating to asset size/geometry | Pigs are generally designed for large diameter pipes. Changes in diameters, including those associated with valves and other fittings, can be an issue |
| | Continuous/discrete | Smart/intelligent pigs provide continuous readings for a variety of factors. |
| | Destructive/non destructive | Non-destructive technique. |
| | Interruption to supply/function | Pigs are propelled by the product flow, so no interruption is required. However, likely to cause quality issues in water mains. Also, there must be appropriate launch facilities for uninterrupted function. |
| Technical suitability | Assessment parameters | Most common requirements are for geometry/diameter measurement and for metal-loss/corrosion. |
| | Integration with software tools | Specialized software tools used to interpret data. |
| | Commercialization of tool | Large number of commercial providers. |
| | Previous/existing use of the tool in sector | Originally developed to remove deposits in pipes. Now used for a wide variety of purposes. Limited use in water sector. |
| | Accuracy/reliability | Quantitative assessment. |
| | Ease of validation of results | Only through visual assessment; though calibration of tools is done. |
| Utility technical capacity | Asset management sophistication required | Associated with high levels of sophistication |
| | Skills required (level of tool sophistication); usability | Smart pigs require trained specialists. |
| | Technology required (level of tool sophistication) | Highly sophisticated tool that requires specialized technology. |
| | Documentation | Large range of product information available. |
| | Availability of technical support | Large number of providers all offering support. |
| Economic factors | Cost per inspection | Relative high cost. |
| | Resource requirements | More advanced pigs require specialists to deploy. |

## F37.7 Bibliography


1. http://www.ppsa-online.com/about-pigs.php, accessed 2005
2. Willke, T. *Five technologies expected to change pipe line industry, Pipe line & gas industry*, vol. 81, No 1, pp. 36-37, 1998
3. Jones, D.G., Dawson, S.J., and Brown, M. *Smart Pigs Assess Reliability of Corroded Pipelines*, Internal Pipeline Corrosion Assessment, Pipeline & Gas Journal, March 1995

# F38.0 KANEW

## F38.1 Overview

KANEW is a software tool used in strategic asset management that estimates lengths of water distribution mains to be rehabilitated or replaced each year.

KANEW contains a network inventory module, a failure and break forecasting module, an economic data module and a strategy comparison module. Through these modules, KANEW predicts when select pipe sections will reach the end of their service lives, differentiated by date of installation and by type of pipe sections with distinctive life-spans.

## F38.2 Main Principles

KANEW is a cohort survival model for infrastructure developed at Karlsruhe University, used to predict future rehabilitation needs for water infrastructure. Based on this approach, Dresden University of Technology developed a Windows based software application called KANEW, which was tested in an AwwaRF Research Project "Quantifying Future Rehabilitation and Replacement Needs of Water Mains" (Arun et al, 1998). Essentially, KANEW evaluates groups of pipes of the same material and diameter (i.e., cohort groups) and estimates the percentage of pipes in each group requiring replacement or rehabilitation each year.

The general framework of the KANEW approach is shown in Figure F-6.

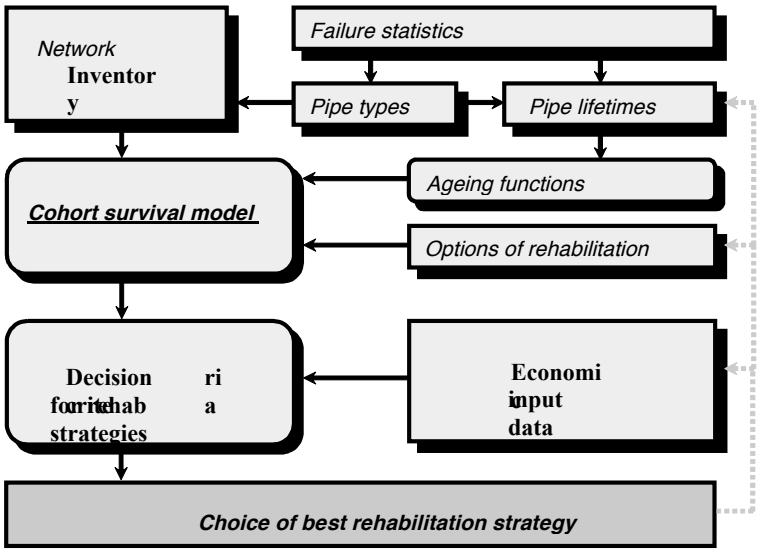


**Figure F-6. Framework for Exploring Network Rehabilitation Strategies**
**(Adapted with permission from Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A-S., and Erickson, M., 2002).**

The tool assumes service-life to be a random variable, starting after some time of resistance and being characterized by a median age and a standard deviation, or age that would be reached by a certain percentage of the most durable pipe section.

KANEW allows the user to calculate residual service lives and annual rehabilitation needs of water pipes on the basis of their specific service life distributions. Specific rehabilitation programs, defined for the medium term, can be analyzed with respect to their economic and other long-range effects. An acceptable strategy is found through an iterative/heuristic process.

## F38.3 Application

KANEW is a Windows based software package, used to predict the future rehabilitation needs for water pipeline networks.

## F38.4 Practical considerations

- KANEW has been used by water authorities in Germany and the United States to assess and develop water main replacement and rehabilitation programs.
- Data availability is a problem in some water utilities. The biggest issue is when there is a data gap in historical water main rehabilitation and replacement. This data is required for estimation of survival functions. As a result, a lack of data would introduce considerable uncertainty into the survival functions for each category of water main.
- Due to this and other sources of uncertainty, the software uses optimistic and pessimistic assumptions to predict an upper and lower range of miles to be rehabilitated or replaced for each category of water mains.
- Version 1.0 is available with user manual for AwwaRF subscribers free of charge and requires Microsoft Access 97 to run. It allows calculation of residual service lives and annual rehabilitation needs of types of water main on the basis of their specific service life distributions.
- The current commercial version is an extended version allowing specific rehabilitation programs to be defined for the medium range and to forecast their economic and other effects on the long range.

## F38.5 Advantages

- KANEW can be used for planning water main rehabilitation and replacement strategies.
- The model can be used both for pipeline renewal planning and for budgeting for future renewals.
- Windows based system that will run on a standard PC

## F38.6 Limitations

- KANEW is a macro model that estimates a broad range of lengths of water mains to be rehabilitated or replaced each year. The model does not predict specific water mains that should be rehabilitated or replaced each year.
- The methodology adopted means that factors such as soil and pressure are not taken into account.

**Table F-40. Summary KANEW.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Water pipes. |
| | Granularity | System and sub-system level only. |
| | Service areas | Potable |
| Technical suitability | Focus of analysis | KANEW is a cohort survival model for infrastructure to predict future rehabilitation needs for water infrastructure. |
| | Scalability of tool/approach | KANEW can be used for planning water main rehabilitation and replacement strategies. The model is useful both for older utilities having an urgent need for renewal plans, and younger utilities budgeting for future renewal plans. |
| | Commercialization | Commercial software available through AwwaRF. |
| | Previous/existing use of the tool | Used by authorities in the United States and in Germany. |
| | Ease of validation | Difficult to validate except by statistical means. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Potable only; cohort to system level. |
| | Integration with other tools/GIS | None. |
| Utility technical capacity | Asset management sophistication | Since good data is required, more associated with higher levels of asset management sophistication. |
| | In-house skills required | Professional engineer. |
| | Technology required | PC based, version 1.0 requires MS Access 97. |
| | Documentation | Tool fully documented. |
| | Data Requirements | Comprehensive data on pipe assets. |
| | Linking to asset data | Linkage through database. |
| | Availability of software and technical support | Available through AwwaRF and commercially. |
| | Usability | KANEW has GUIs and is capable of providing 13 different sets of graphical and tabular outputs. |

## F38.7 Bibliography


1. Baur, R. and R. Herz *Proceedings of the 13th European Junior Scientist Workshop held at Dresden University of Technology* on "Service life management of water mains and sewers". ISBN 3-86005-238-1, 1999
2. Deb, A.K., Hasit, Y.J., Grablutz, F.M. and Herz., RK. *Quantifying future rehabilitation and replacement needs of water mains*. AwwaRF Research Report, 1998
3. Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A-S., and Erickson, M. *Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems*, EPA, EPA/600/R-02/029, 2002

# F39.0 KureCAD

## F39.1 Overview

KureCAD was developed by the Viatek Group in Finland and uses a GIS to assist in the management of sewer pipe network rehabilitation. The system can store information on all infrastructure assets, prioritize the rehabilitation of pipes, and provide the necessary documents to implement rehabilitation.

## F39.2 Main Principles

Once the KureCAD system contains all the necessary data, it enables managers to assess system conditions and prioritize work. For each pipe section, the system enables users to record three basic types of data:

- Structural condition (strength and shape).
- Functional condition (its ability to transport water).
- Leakage rates (estimated leakage from the pipe).

Users can employ data from internal inspections or maintenance records to summarize the pipe's condition by assigning a score from 1 (good, no repairs required) to 4 (very bad, needs to be repaired immediately). Users can also rate each pipe using other factors.

The system records whether the entered data is based on estimates or actual inspections. The KureCAD system then combines all of the condition scores into one condition index which is displayed via the GIS.

## F39.3 Application

KureCAD is used to assist asset managers in identifying and prioritizing the repair/rehabilitation of sewer pipes.

## F39.4 Practical considerations

- KureCAD is still under development but has been trialed in Europe. As the user interface is based on GIS, a digital map of the network is required.
- The KureCAD system provides instruction to ensure consistency for data collection during field inspections and maintenance.

## F39.5 Advantages

- GIS approach to managing data and providing decision support.
- The KureCAD software is able to generate the paperwork necessary to initiate repair/rehabilitation work, including detailed maps specifications.

## F39.6 Limitations

- The tool is still in its development stages and at this point in time has only been trialed in Europe.
- If GIS data is not available then maps have to be manually digitized.

**Table F-41. Summary KureCAD.**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Sewer pipes. |
| | Granularity | System and asset level. |
| | Service area | Wastewater |
| Suitability | Focus of analysis | Uses GIS to manage sewer pipe rehabilitation. Prioritizes the rehabilitation of pipes and provides the necessary documents to implement the rehabilitation. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good GIS data is available. |
| | Commercialization | Commercial software available from Viatek Finland. |
| | Previous/existing use of the tool | Used by several Scandinavian authorities. |
| | Ease of validation | Difficult to validate except by statistical means. |
| | Flexibility with respect to analysis (asset types) and granularity (system, asset level) | Wastewater; asset to system level. |
| | Integration with other tools/GIS | Integrates with GIS system. |
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management where GIS data is available. |
| | In-house skills required | Professional asset manager/engineer. |
| | Technology required | PC based tool. Windows based operating system. |
| | Documentation | Product in development. |
| | Data Requirements | GIS data required. |
| | Linking to asset data | Through pipe IDs. |
| | Availability of software and technical support | Unknown. |
| | Usability | Still under development. |

## F39.7 Bibliography

1. Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A-S., and Erickson, M. Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems, EPA, EPA/600/R-02/029, 2002

# F40.0 Leak Detection

## F40.1 Overview

Water loss control programs are widely used throughout the water industry and a major phase of these programs is leak detection. Leak detection is used to determine the exact location of a leak in a pipeline. The repair of leaks saves revenue and conserves water and energy.

Leak detection is currently undertaken using a number of techniques, including acoustic techniques, tracer gas and infrared photography. Drop tests and in-pipe hydrophones are also used and are discussed in separate reviews (see Drop Test and In-Pipe Hydrophones reviews).

Leak detection gives an indication of condition and performance of a network or asset, depending upon the amount of leaks found.

District metered areas (DMA) are used to aid with leak detection of the distribution system. Also, because DMAs can encompass portions of the transmission system, this approach is also used as an aid to locating transmission system leaks.

## F40.2 Main Principles

Leak detection is generally conducted after primary and secondary surveys that assess areas of a network to determine their level of leakage, which is used to identify specific areas in need of further investigation. Once small areas of the network have been identified as containing significant leaks (through the use of various techniques, including data logging, district meter area data audits, and monitoring of night flows), these are surveyed in more detail to determine the exact location of the leaks.

A common technique to determine the location of leaks uses acoustic sensors to detect the noise/vibration made by water escaping the pipe under pressure. Leaks generally make three sounds, a medium frequency sound, 500-800 Hz, associated with the water passing through the orifice/leak and two low frequency noises, 20-300 Hz, associated with the water stream impacting the soil and circulating outside of the pipe (Burn et al, 1999). Acoustic techniques can not detect very small leaks such as weeping and seepage from cracks and joints, commonly referred to as background leaks.

There are two principal methods of detecting sounds from leaks; noise correlators and data loggers:

- ***Noise correlators*** are computer controlled systems that measure noise at either side of the suspected leak location and locate the leak automatically.
- ***Data loggers*** consist of units containing audible leak detection hardware coupled with a data logger, radio transmitter and extended life battery (10+ years). These units are installed at multiple locations around a pipe network for extended periods (from overnight to indefinitely) and the data collected by the inspection team at regular intervals.

While leak detection by this method can be conducted regardless of the pipe material, plastic pipe materials tend to be “quieter” than metallic or cementituous materials and so make it harder to detect leaks using acoustic methods.

Techniques such as the tracer gas are not yet widely used in the water industry. The tracer gas technique involves the introduction of a non-toxic water-insoluble lighter-than-air gas such as hydrogen or helium into the pipe system. These tracer gases escape at leaks and

permeate through the cover soil and pavement to be located by specialized gas detectors above the leak.

The infrared photography technique or thermography is more commonly used and is based on water having different thermal characteristics to the surrounding soil and in turn act like a heat sink relative to the soil. Infrared scanners are the used to detect thermal anomalies outside of the pipes. Devices used for this can be either hand held or vehicle mounted (Burn et al 1999).

The use of thermography from fixed or rotary wing aircraft can identify potential areas of leakage from water mains. The technique detects ground water anomalies (water escaping from the main creates 'wet' patches on the ground) through infrared thermography. Arial thermography can potentially cover large areas relatively quickly. The technique is limited by ground conditions (it is not recommended in urban areas), the line of the main, the local ground temperatures (compared to the water temperature), and local drainage.

Arial thermography can potentially cover large areas relatively quickly. In practice, the aircraft has to fly a straight line along the main. At every change in course of the pipeline, a fixed wing aircraft has to circle in order to obtain a level approach to the new line. Helicopters are not limited as much because they can fly at lower levels and execute level turns, but unit cost for helicopters are higher.

## F40.3 Application

Large leaks in water distribution networks can be identified quickly as the amount of water flowing from the pipe has noticeable affects at ground level. However, pipe assets which contain small leaks do not release enough water for surface affects to be seen at ground level. Leak detection techniques are used to locate these leaks.

- There are no a standards for Leak Detection.

## F40.4 Practical considerations

- Leakage testing is widely used, both in the water and many other industries, although techniques used vary.
- Generally all techniques require some level of operator skill to obtain reliable results.

## F40.5 Advantages

- Active leak detection allows leaks that would otherwise have gone unnoticed to be found.
- Data logging techniques can be used to focus the search for leaks.
- Arial thermography can potentially cover large areas relatively quickly.

## F40.6 Limitations

- Noise correlators and data loggers are less suited for use on non-metallic pipe materials due to the pipe's low sound propagation properties.
- Detection success is sensitive to background noise levels.
- Acoustic detectors do not detect weeping type small leaks.

**Table F-42. Summary Leak Detection.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes. |
| | Material type | All, effectiveness depends on technique used. |
| | Service area | Potable. |
| | Access requirements | Noise correlators require access to the pipe; fire hydrants are sufficient. Data loggers may need to be located 'on' pipes, requiring excavation. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Continuous readings can be achieved. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Assessment should be conducted on-line. |
| Technical suitability | Assessment parameters | Locates leaks. |
| | Integration with software tools | Software packages used to interpret data |
| | Commercialization of tool | Tools are widely available in industry. |
| | Previous/existing use of the tool in sector | Techniques and tools are widely used. |
| | Accuracy/reliability | Quantitative or semi-quantitative; accuracy is dependant on the technique used. |
| | Ease of validation of results | Validated by exhuming the asset. |
| Utility technical capacity | Asset management sophistication required | Higher levels of asset management sophistication will generally result in more efficient inspections but it is not required. |
| | Skills required (level of tool sophistication); usability | Operator needs to trained. |
| | Technology required (level of tool sophistication) | The level of technology required depends on the technique to be used. |
| | Documentation | Techniques widely documented |
| | Availability of technical support | Tools are supported by suppliers and by consultants. |
| Economic factors | Cost per inspection | Depends on technique. |
| | Resource requirements | Requires teams to conduct surveys, actual manpower depends on technique to be used. |

## F40.7 Bibliography


1. Burn. L. S., DeSilva. D., Eiswirth. M., Hunaidi. O., Speers. A. and Thornton. J. *Pipe Leakage – Future Challenges & Solutions*, Pipes Wagga Wagga, 1999

2. Chastain-Howley, A (2005) *Transmission Main Leakage: How to reduce the risk of a catastrophic failure*, Leakage 2005 - Conference Proceedings

3. Dingus, M., Haven, J. and Austin, R. (2002) *Nondestructive None Invasive Assessment of Underground Pipes*, AwwaRF, USA

4. Eiswirth, M., Burn, L.S. (2001) *New Methods for Defect Diagnosis of Water Pipelines*, 4th International Conference on Water Pipeline Systems, 28-30 March, York, UK, 2001

5. http://www.owue.water.ca.gov/leak/leaktech/leaktech.cfm, accessed 2005.

6. Makar, J. M. ; Chagnon, N. *Inspecting systems for leaks, pits, and corrosion*, National Research Council of Canada, Institute for Research in Construction, NRCC-42802, 1999 (downloaded from www.nrc.ca/irc/ircpubs)

## F41.0 Linear Polarization Resistance of Soil (Soil LPR)

### F41.1 Overview

Linear Polarization Resistance of soil (LPR) is a characteristic used to predict the corrosion rate of buried ferrous assets. LPR has a negative correlation with corrosion rate in ferrous assets, meaning that soils with high LPR values will exhibit low corrosion rates.

The empirical relationship between LPR and corrosion rate was initially investigated for cast iron, establishing a base relationship between corrosion rate and LPR. In a subsequent study for wrought iron, a much weaker relationship was established, and there was too much variation in measurements to fully establish a correlation. Consequently there is some debate over the usefulness of LPR for materials other than cast iron.

### F41.2 Main Principles

LPR is measured for soil samples obtained from near the location of interest, usually a buried asset or its future location. Several methods are available for measurement of LPR, the simplest of which will be described here. The soil samples are brought to their wilting point before testing (the wilting point is defined as the soil moisture content at which plants are unable to extract water and varies with soil type). A small potential is applied across two 'identical' electrodes in a cell containing the prepared soil sample. The current at each electrode is measured. This measurement is repeated over a range of potentials.

The resulting relationship between current and applied potential is called the polarization curve. The reciprocal of this curve at the corrosion potential is called the polarization resistance, where the corrosion potential is the potential that exists between a metal and its environment (see Soil (electrical) Resistivity review). Different metals can have different polarization resistance values in the same soil type. The linear polarization resistance is taken from the region where the polarization resistance curve is considered to be linear and can be applied to numerous metals without specific knowledge of their corrosion potential in the soil being tested.

### F41.3 Application

LPR is used to indirectly determine the corrosion rate of buried ferrous assets using an empirical relationship.

- No standards are known to directly reference this technique; however AS/NZS 2280:2004 does mention its use.

### F41.4 Practical considerations

- Equipment that can be used for determining LPR (probes) is widely available and come with two or more probes. Additional probes are intended to reduce error in readings. The accuracy of readings is dependant on equipment used and sample preparation.
- The sample preparation requirements generally require testing be conducted in a laboratory.

### F41.5 Advantages

- Low cost technique.
- LPR is a simple method which can be used to give an indication of corrosion rate.

## F41.6 Limitations

- There is disagreement as to the reliability of the method and the relationship with corrosion rate is empirical only.
- The assumption of linearity is not always representative of real conditions and so reduces the accuracy of the technique.

**Table F-43. Summary Linear Polarization Resistance of Soil (Soil LPR).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Environmental survey (pipeline assets). |
| | Material type | Results relate to ferrous assets. |
| | Service Area | Potable and wastewater. |
| | Access requirements | Access to soil at point of interest. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Results are discreet. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Test does not affect assets. |
| Technical suitability | Assessment parameters | Soil linear polarization resistance (LPR). |
| | Integration with software tools | None. |
| | Commercialization of tool | Equipment is widely available. |
| | Previous/existing use of the tool in sector | Currently being used in Australia as a screening approach to corrosion. |
| | Accuracy/reliability | Information on accuracy of the technique is varied and can depend on measurement method. |
| | Ease of validation of results | Validation by assessment of the asset. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Operator training is required. |
| | Technology required (level of tool sophistication) | Specialized equipment required. |
| | Documentation | Technique described well in literature. |
| | Availability of technical support | Information available in literature. |
| Economic factors | Cost per inspection | Low cost. |
| | Resource requirements | Measurements undertaken by a single person. |

## F41.7 Bibliography


1. Burn, L.S., Eiswirth, M., DeSilva D. and Davis P., *Condition Monitoring and its Role in Asset Planning*, Pipes Wagga Wagga 2001, Charles Stuart University, Wagga Wagga, N.S.W., 2001
2. Heathcote, M. and Nicholas, D., *Life Assessment of Large Cast Iron Watermains*, Urban Water Research Association of Australia, Research Report No 146, 1998
3. Moglia M., Davis P., Farlie M. and Burn S. *Indirect Measurements of Corrosion rates in buried Wrought Iron pipelines: an application of Linear Polarization Resistance,* 6th National Conference of the Australasian Society for Trenchless Technology, Melbourne Exhibition and Convention Centre. 27-29 September 2004
4. AS/NZS 2280:2004, Ductile iron pipes and fittings

# F42.0 Load Rejection Tests

## F42.1 Overview

Power generation systems can experience sudden changes in load as a result of an emergency shutdown, failure of equipment or changes in consumer power demand. Load rejection tests or models are intended to analyze and predict the performance of power generation systems under these sudden load changes.

Either full load rejection tests or partial load rejection tests can be conducted. However, many tests attempt to examine full load rejection since this is the worst case scenario.

## F42.2 Main Principles

Load rejection tests are most commonly applied to power generation systems such as hydro-power plants, wind turbines and steam turbine power plants. When undertaking load rejection assessment, analysis may either be carried out on the actual plant or modeled using commonly available computer software programs developed for undertaking load rejection analysis. In order to create a computer model, an adequate amount of information and data on the operating characteristics of the plant needs to be collected, such as turbine characteristic curves, penstock construction details and any available hydraulic transient test data.

An example of a load rejection event would be if the load on a hydro-powered generator is suddenly removed, as a result the turbine will rapidly accelerate the generator before the turbine governor has time to correct the turbine speed. The occurrence of such an event could have a catastrophic impact, if sufficient controls are not in place to deal with this type of load rejection. Within a hydro-power station, a relief penstock is usually available to divert water away from the turbine in the case of load rejection event.

## F42.3 Application

Load rejection assessments are often conducted or simulated using computer programs, to gain an understanding of the effects of power station performance when sudden load changes are found to occur.

- Load rejection tests are covered in the National Grid Code, United Kingdom and the Transmission Code 2003, Germany.

## F42.4 Practical Considerations

- Technical staff that are trained and have experience in undertaking, assessing and simulating load rejection events are required.

## F42.5 Advantages

- By undertaking load rejection tests, the risks and consequences associated with the event of sudden load rejections of power generation systems can be determined.

## F42.6 Limitations

- When modeling load rejection events using computer simulation programs, the time in setting up a computer model is often time consuming.

**Table F-44. Summary Load Rejection Tests.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Generators. |
| | Material type | N/A |
| | Service area | Potable and wastewater. |
| | Access requirements | Access requirements will be site specific. |
| | Limitations relating to asset condition | Before a load rejection test is performed on an actual plant, a hazard identification and risk assessment is carried out. This will be site specific and should take into consideration the condition of the plant. |
| | Limitations relating to asset size/geometry | No restrictions. |
| | Continuous/discrete | Continuous. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | On-line. |
| Technical suitability | Assessment parameters | Turbine overspeed, penstock pressures, structural adequacy of surge tanks, pipelines, penstocks, etc. |
| | Integration with software tools | Load rejection tests would usually be carried out as stand alone tests. |
| | Commercialization of tool | Tests need to be developed so that they are site specific. |
| | Previous/existing use of the tool in sector | Commonly used in the power generation industry; limited use in water sector. |
| | Accuracy/reliability | Dependent on the instruments used to record data. |
| | Ease of validation of results | Computer models can be calibrated using hydraulic transient test data. |
| Utility technical capacity | Asset management sophistication required | High level of AM sophistication. |
| | Skills required (level of tool sophistication); usability | Usually a team of engineers would be required to design and carry out the tests. |
| | Technology required (level of tool sophistication) | Reasonably high powered computers are required to run the computer software models. |
| | Documentation | No current ASTM standards. |
| | Availability of technical support | There are suitable software packages available with customer support. |
| Economic factors | Cost per inspection | Expensive. |
| | Resource requirements | Usually a team of engineers would be required to design and carry out the tests. |

## F42.7 Bibliography


1. Rebizant, W. & Terzija, V. *Asynchronous Generator Behavior after a Sudden Load Rejection*, http://zas.ie.pwr.wroc.pl/wr_bpt03-2.pdf, accessed 2006
2. Tzuu Bin Ng, Walker, G.J. and Sargison, J.E. Mo*deling of Transient Behavior in a Francis Turbine Power Plant*, The University of Tasmania, Hobart, www.aeromech.usyd.edu.au/15afmc/proceedings/papers/AFMC00084.pdf

## F43.0 LPR for Corrosion Monitoring

### F43.1 Overview of Tool

Linear polarization resistance (LPR) corrosion monitoring equipment measures corrosion rate directly. The probes come in many types for embedding in new infrastructure, retrofitting to existing infrastructure and a surface probe for more impromptu inspection.

### F43.2 Main Principles

Linear polarization resistance is measured by passing a small current from the auxiliary electrode to shift the potential of the steel by a fixed amount. The polarization resistance is the potential shift divided by the current applied. It is inversely proportional to the corrosion rate. Faraday's Law can be used to convert the corrosion rate current in $\mu A/cm^2$ to steel section loss in microns per year. A section loss rate of approximately100 microns will cause cracking and spalling of concrete.

Probes measure the polarization resistance, which approximately relates to actual corrosion rate of steel reinforcement in existing concrete structures.

### F43.3 Application

Linear polarization resistance has been used in tunnels, bridges and road decks in the United Kingdom, Singapore and India since 1998. Often linear polarization resistance measurements are obtained in conjunction with electrical potential and/or concrete resistivity.

- The LPR technique is described in ASTM G59.
- Practical considerations.
- A range of corrosion monitoring probes are available. Probes can be located in core holes that are retrofitted into existing structures. Probes use silver/silver chloride reference half cells with mixed metal oxide coated titanium auxiliary electrodes. The probe is fitted into a core hole and a connection is made to the reinforcement using the probe flying lead. An electronic identification chip within the probe identifies the probe and its physical location to the corrosion rate meter or to an automated data logging system.
- Other corrosion monitoring probes include: a rack of probes that can be embedded during the construction of new concrete structures; hand held probes that allow surfaces to be monitored manually.
- An embedded rack of probes can measure the corrosion rate and corrosion potential for a single element probe and the reinforcement, as well as the concrete resistivity and concrete temperature. It is designed to monitor new structures where deterioration of the structure or initiation of corrosion is of interest.
- Multi condition rack probes have been designed to provide information over a varying depth profile. Four independent linear polarization resistance electrodes at varying levels of concrete cover allow the determination of corrosion rate and half potential for the element probes and the reinforcement. Concrete resistivity at three points, temperature, and the derivable rate of ingress of corrosive substances can also be determined.
- Working similar to a potentials survey, a connection to the reinforcement is made and then measurements can be taken up to 25m from the connection. The mobile probe uses

conductive foam to control the spread of current. Probes come in a range of sizes. Small probes are useful for tight fitting areas; however large probes give greater accuracy.

- It is useful to measure the temperature in different areas of a concrete structure in order to determine differential temperature gradients and their affect on a concrete structure's long-term performance.

## F43.4 Advantages

- Hand held mobile probes allow linear polarization resistance measurement to be carried out at any position on the structure chosen by the user.
- Surveys of structures can readily be made in dry and wet situations to model best and worst-case scenarios.
- LPR data loggers can be integrated with corrosion data management software. By inputting rebar alloy density, dimensions and exposure data, the software can calculate metal loss and corrosion rate.

## F43.5 Limitations

- Testing often requires that at least two holes in the order of 6.5mm to variable depths drilled in order to insert probes.
- It is important that sufficient time is allowed for a current value to stabilize at a certain potential (or vice versa). For example, in certain LPR techniques such as potentiostatic, it will typically take several minutes for the current to reach a stable level after the polarizing voltage is applied. Shorter times could lead to significant measurement errors.
- Some LPR testing technologies such as testing apparatus with a guard ring do not allow quick assessing of large concrete surface areas. To reduce evaluation times to acceptable, practical levels, the corrosion potential values can be mapped, followed by a selective application of such testing apparatus to critical areas.

**Table F-45. Summary LPR for Corrosion Monitoring.**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Reinforced concrete structures such as tanks, pipes, walls, dams, buildings, channels, weirs. |
| | Material type | Reinforced concrete. |
| | Service area | Potable and wastewater. |
| | Access requirements | Direct contact with surface of asset. If asset is buried then it must be exposed. |
| | Limitations relating to asset condition | No restriction. |
| | Limitations relating to asset size/geometry | No limitations relating to size of concrete element. |
| | Continuous/discrete | Continuous reading. |
| | Destructive/non destructive | Almost entirely non destructive, small drill holes required. |
| | Interruption to supply/function | The asset can remain in use and does not need to be taken off-line unless internal (water side) surfaces need to be assessed. |
| Technical suitability | Assessment parameters | Concrete temperature that in turn allows differential temperature gradients and their affect on a concrete structure's long-term performance to be determined. |
| | Integration with software tools | The data can be transmitted to a central location using telemetry. |

| | Criteria | Assessment |
|---|---|---|
| | Commercialization of tool | Equipment is fully developed, available from selected commercial vendors and can be used off the shelf. |
| | Previous/existing use of the tool in sector | Widespread use internationally on bridges and road infrastructure. Growing application in the water industry. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Results are indicative and can be validated by using two other testing techniques: concrete electrical resistance and rebar electrical potential. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Relatively easy to use by following simple procedure. Trained staff can take measurements. Linear polarization resistance meters do not require specialist knowledge or training. |
| | Technology required (level of tool sophistication) | Range from moderate to high level of sophistication. Many automatic corrosion transmitters are capable of measuring and transmitting data from all types of corrosion probes. Optional technology includes programmable alarm circuits. |
| | Documentation | ASTM G59. Further guidelines specifically for on-line in-plant corrosion monitoring are given in ASTM G96. |
| | Availability of technical support | Technical support available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. LPR uses a series of electrodes, a voltmeter, an ammeter and a current source. |

## F43.6 Bibliography

1. ASTM G59-97(2003) Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements

# F44.0 Magnetic Flux Leakage

## F44.1 Overview

A magnetic flux leakage (MFL) tool is an electromagnetic tool that identifies and measures metal loss due to corrosion, physical damage, and so forth through the detection of a temporarily applied magnetic field. The tool provides a non-destructive means of assessing ferrous pipes. Tools using the same principle are available for inspecting tank floors.

As illustrated in Figure F-7, as the tool moves along the pipe, it induces a magnetic flux in the pipe wall. A homogeneous steel wall – one without defects – creates a homogeneous distribution of magnetic flux. Anomalies such as metal loss associated with corrosion of the pipe wall result in a change in distribution of the magnetic flux, which, in a magnetically saturated pipe wall, leaks out. Sensors onboard the tool detect and measure the amount and distribution of the flux leakage. The flux leakage signals are processed, and resulting data is stored onboard the MFL tool for later analysis and reporting.

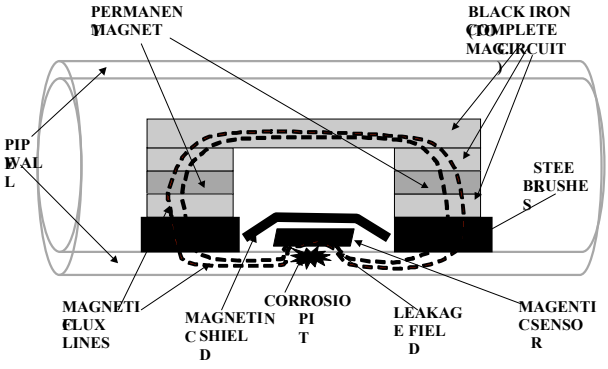


**Figure F-7. Schematic Representation of MFL Internal Detection Device.**

A transverse MFL/transverse flux inspection (TFI) tool uses the same principal as other MFL tools with the exception that the magnetic field is oriented perpendicular to that used in the other techniques.

## F44.2 Main Principles

Typically, an MFL tool consists of two or more bodies. One body is the magnetizer with the magnets and sensors and the other bodies contain the electronics and batteries. On the very rear of the tool are wheels that travel along the inside of the pipeline to measure the distance and speed of the tool.

A strong magnetic field is established in the pipe wall; brushes typically act as a transmitter of magnetic flux from the tool into the pipe. High field MFL tools saturate the pipe wall with magnetic flux until the pipe wall can no longer hold any more flux. The remaining flux leaks out of the pipe wall and strategically placed sensor heads measure the leakage field. Damaged areas of the pipe can not support as much magnetic flux as undamaged areas, resulting in an increase in the flux field at the damaged areas. An array of sensor around the circumference of the tool detects the magnetic flux leakage and notes the area of damage.

Magnetic flux leakage is a vector quantity and the sensors can only measure in one direction. As such, three sensors must be oriented within a sensor head to accurately measure the axial, radial and circumferential components of an MFL signal (earlier MFL tools recorded only the axial component).

With large diameter pipes, space is available for multiple magnet arrays that can saturate the entire pipe circumference. However, since the mass of the magnets and backing steel need to be greater than the pipe wall, it has not been possible to develop internal tools to suit small diameter distribution pipes.

Direct contact with the pipe wall is required. As such, the pipe surface must be clean. The tool is mounted on a wheeled carriage and connected to an umbilical cord. Larger units have onboard computers and power; an umbilical cord is not required.

Access has to be provided by cut-ins at regular intervals depending on the umbilical length, as well as bends and obstructions in the pipeline.

The TFI tool is used to determine the location and extent of longitudinally-oriented corrosion. This makes TFI useful for detecting seam-related corrosion. Cracks and other defects can be detected also, though not with the same level of reliability. A TFI tool may be able to detect axial pipe wall defects – such as cracks, lack of fusion in the longitudinal weld seam, and stress corrosion cracking – that are not detectable with conventional MFL and ultrasonic tools. External units are available for small diameter pipes.

## F44.3 Application

MFL tools detect corrosion in ferrous pipelines. MFL detectors are generally used in the oil and gas industry, incorporated into intelligent pigs for metal loss detection in steel pipelines (see intelligent pigs review). The MFL probes are bulky and heavy and not suitable for internal use in small diameter pipes.

Although commonly used in internal inspection, they have been adapted for external inspection of pipes including water pipes. The external units are available for small diameter pipes.

Tools using the same principle are available for inspecting tank floors.

## F44.4 Practical considerations

- This technique is used in the oil and gas industry for large diameter pipelines. Sophisticated electronics on board allow this tool to accurately detect features as small as 1 cm by 1 cm.
- To more accurately predict the dimensions (length, width and depth) of a corrosion feature, extensive testing is performed before the tool enters the pipeline. Using a known collection of measured defects, tools can be trained and tested to accurately interpret MFL signals.
- There is limited data available from the water industry as the degree of detail and accuracy achievable with these tools is not generally warranted for water pipelines.

## F44.5 Advantages

- When used in the oil sector, accurate assessment of pipeline defects improves decision making within an Integrity Management Program. Excavation programs can then focus on required repairs instead of calibration or exploratory digs.
- Units used on the pipe external surface can be used without supply interruption.
- Wall thickness reductions detected with a high degree of accuracy.

## F44.6 Limitations

- The magnetic flux leakage techniques used in oil and gas pipe inspection have proven ineffective for water pipes.

- Internal inspection requires pipe cleaning prior to inspection. Pipe has to be off-line and dry.
- Cost is significantly high corresponding to the accuracy, which is not generally warranted in the water sector.
- As MFL techniques require good magnetic contact with the pipe wall internal inspection is not possible for cement lined pipelines unless the lining is removed.

**Table F-46. Summary Magnetic Flux Leakage.**

| | Feature | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes and tank floors. |
| | Material type | Iron and steel. |
| | Service area | Potable and wastewater. |
| | Access requirements | Tool available for internal and external use. Direct contact with pipe wall required. Access to tool has to be provided by cut-ins at regular intervals depending on umbilical cord feed length and bends and obstructions on pipeline. Regularly spaced cut-ins not required for larger units with on-board computers and power. |
| | Limitations relating to asset condition | No limitations relating to asset condition provided direct contact with the pipe wall is available; when used internally, pipes can not be lined. Pipe surface must be clean. |
| | Limitations relating to asset size/geometry | Internal tools: generally limited to pipes 250 mm and greater. External tools: 150 mm and larger. |
| | Continuous/discrete | Continuous readings. |
| | Destructive/non destructive | Non-destructive, though tool access requires cut-ins at regular intervals (100 m to 500 m, depending on cable length, pipe alignment). |
| | Interruption to supply/function | Internal requires pipe to be off-line. |
| Technical suitability | Assessment parameters | Metal loss due to corrosion or physical damage. |
| | Integration with software tools | Computerized software is used for data interpretation. |
| | Commercialization | Commercialized, but availability through specialized companies engaged in this work. |
| | Previous/existing use of the tool | Commercial use of the MFL probes reported in literature and trade journals. |
| | Accuracy/reliability | Accurate quantitative assessments possible. |
| | Ease of validation | Validation possible only by comparison with manual /direct measurements. |
| Utility technical capacity | Asset management sophistication | More suited to sophisticated utilities. |
| | Skills required (level of tool sophistication); usability | Utility should have skills to interpret output data. Tool operation typically by a third party. |
| | Technology required | Specialized equipment and dedicated computer software. |
| | Documentation | Tool principles and description of reports generated by tool will be available. |
| | Availability of technical support | Service provided by special operator. |
| Economic factors | Cost per inspection | Greater than US$10,000 per site, plus civil costs. |
| | Resource requirements | Typically three person crew. |

## F44.7 Bibliography


1. Burn, L.S., Eiswirth, M., DeSilva D. and Davis P., *Condition Monitoring and its Role in Asset Planning*, Pipes Wagga Wagga 2001, Charles Sturt University, Wagga Wagga, N.S.W., 2001
2. Eiswirth, M., Burn, L.S. *New Methods for Defect Diagnosis of Water Pipelines*, 4th International Conference on Water Pipeline Systems, 28-30 March 2001, York, UK, 2001
3. Makar, J. M. ; Chagnon, N. *Inspecting systems for leaks, pits, and corrosion*, National Research Council of Canada, Institute for Research in Construction, NRCC-42802 (downloaded from www.nrc.ca/irc/ircpubs), 1999
4. Trenchless Technology Network *Underground Mapping, Pipeline Location Technology and Condition Assessment*, (downloaded from http://www.ttn.bham.ac.uk/Final%20Reports/Pipe%20Location%20and%20Assessment.pdf accessed 2006), 2002
5. Makar, J. M. ; Chagnon, N. *Inspecting systems for leaks, pits, and corrosion*, National Research Council of Canada, Institute for Research in Construction, NRCC-42802 (www.nrc.ca/irc/ircpubs, 1999

## F45.0 Man Entry Inspection

### F45.1 Overview

While CCTV is now the industry standard approach for inspecting the internal condition of sewers, in larger diameter sewers it becomes economical to carry out man entry inspections. In this approach, the internal condition of the asset is assessed using a walk-through inspection technique. This requires a team of operatives to enter the pipeline, and assess the condition of the manhole and the sewer walls above the flow line.

Defects are assessed visually and recorded along with distance using a standard coding system. Photographs of features of interest can also be taken. When this is done, the picture reference should ideally be cross-referenced with the survey distance. Hand held videos can also be used to provide a permanent record of the inspection.

The safety implications of man-entry inspections should be given appropriate consideration. In particular, when entering a manhole sewer line, it is very important to observe the appropriate confined space regulations.

### F45.2 Main Principles

A man entry condition assessment is conducted as a walk through inspection. Since sewers are hazardous confined spaces, manholes are first vented and tested for gases such as hydrogen sulfide. When conditions are confirmed as being safe, a team of operatives carries out the survey using appropriate safety equipment (e.g., gas detectors, breathing apparatus, harnesses, winches, protective clothing, and communication systems).

During the inspection, the crew assesses the appearance of the sewer, the presence of flow disturbances, the extent of corrosion, and the structural condition of the sewer. Photographs should be taken of any observed defects, and a hand-held video camera can also be used to videotape the internal surface of the sewer.

Acoustic tests may also be performed by striking the crown, sidewalls, and invert of the sewer with a hammer and noting whether the generated sound is dull or solid. This provides qualitative information regarding the sewer structure and, depending on construction, can indicate the presence of voids in the sewer wall.

Other inspection techniques can be applied depending on material; for example, the use of cover meters in reinforced concrete sewers. To assess the extent of corrosion activity, field measurements of pH, dissolved oxygen, ambient hydrogen sulfide, and dissolved hydrogen sulfide may also be taken.

### F45.3 Application

Man-entry inspections are performed on large-diameter sewer pipelines and tunnels. This kind of inspection can also be undertaken on large diameter water pipelines.

- A number of systems are used for sewer condition grading, a Standard version of which is EN 13508-2:2001 (CEN 2001).

### F45.4 Practical considerations

- Man entry inspections are a commonly applied technique in the water sector, and inspection services are supplied by specialist contractors. However, due to the hazardous conditions in the sewer and confined space requirements, safety precautions are paramount, in particular:

- If the flow of wastewater cannot be diverted, inspections should be performed at night and during dry weather conditions so that the flow is minimal.
- Ventilation fans should be used to ensure good ventilation.
- During the survey, the atmosphere should be constantly monitored and emergency evacuation procedures strictly adhered to.
- The inspection should be performed by at least two persons and they should have constant communication with the personnel outside the sewer line.

- The crew who carry out the inspection should be trained in order to ensure consistency and uniformity of the inspection results.
- For wastewater pipelines, standards are available for qualitative and quantitative grading of defects and a system for condition grading commonly used. Condition assessment is performed by allocating a grade to the sewer that represents the range of conditions from "like new" to "collapsed" or "collapse imminent." The accuracy of a condition grading depends on the inspector's experience.

## F45.5 Advantages

- Man entry inspection is cost-effective for the inspection of large diameter pipelines.

## F45.6 Limitations

- There are significant health and safety issues associated with the inspection; all operatives must be fully trained in safety requirements.
- The results are qualitative and require manual interpretation for analysis.
- The accuracy of a condition grading depends on an inspector's experience.

**Table F-47. Summary Man Entry Inspection.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Pipelines. |
| | Material type | Any. |
| | Service area | Potable and wastewater. |
| | Access requirements | Man entry access required. |
| | Limitations relating to asset condition | Must be safe to access. |
| | Limitations relating to asset size/geometry | Man entry access required. |
| | Continuous/discrete | Continuous. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Flow must be minimized, but inspection can be undertaken on-line. |
| Technical suitability | Assessment parameters | Pipeline defects. |
| | Integration with software tools | None. |
| | Commercialization of tool | Service is provided by specialized contractors. |
| | Previous/existing use of the tool in sector | Common approach. |
| | Accuracy/reliability | Qualitative assessment of condition. |
| | Ease of validation of results | Direct observations. |

| | Criteria | Assessment |
|---|---|---|
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Inspectors must be trained in confined spaces and condition assessment. |
| | Technology required (level of tool sophistication) | Low tech inspection, but high tech safety equipment. |
| | Documentation | No. |
| | Availability of technical support | No. |
| Economic factors | Cost per inspection | High personnel and mobilization costs. |
| | Resource requirements | Team size in line with confined spaces regulations. |

## F45.7 Bibliography


1. ASCE, Sanitary Sewer Overflow Solutions, American Society of Civil Engineers, EPA Cooperative Agreement CP-828955-01-0, April 2004
2. European Committee for Standardization EN 13508-2:2001 *Condition of Drain and Sewer Systems Outside Building – Part 2: Visual Inspection Coding System*, CEN Brussels, 2001

# F46.0 Measurement of Strain

## F46.1 Overview

Several techniques are used to measure strain of assets; electrical resistance strain gauges and photoelastic techniques are discussed herein.

## F46.2 Principles

### Electrical Resistance Strain Gauge

The electrical resistance strain gauge is the most common type of strain gauge used today. This simple strain gauge consists of a very fine wire filament (a resistor) arranged in a long zig-zag pattern, with the long lengths parallel to the measured strain. The fine wire is bonded to the strained surface by a thin layer of epoxy resin. As the surface and hence the wire filament is strained, the wire will become elongated and the diameter will reduce. The reduction in diameter will cause the resistivity of the wire to increase. An electrical signal passed through the filament will vary depending on the strain.

'Gauge Factor' is a parameter equal to the fractional change in electrical resistance divided by the actual strain. Since the magnitude of strain rarely exceeds the order of $10^{-3}$ and the Gauge Factor is often about 2, the fractional change in electrical resistance can be extremely small. This means that the measurements need to be extremely accurate to avoid errors. To improve the accuracy of the measurements, the strain gauge is inserted into an electric circuit such as the Wheatstone bridge.

### Photoelastic Strain Gauge

A birefringent material is a transparent material such as calcite crystal that exhibits two different refractive indices. The polarization of the light traveling through the material determines the extent each refractive index plays.

A photoelastic material is a material that only exhibits the property of birefringence when the material is under stress. A polarized light beam traveling through a stressed photoelastic material will be resolved into two components such that the electric field vector in each component is aligned with one of the two principal stress axes in the material. Each component of the light beam will experience a different refractive index, causing the two components to travel at different speeds and thus be out of phase with each other when they exit the photoelastic material. Photoelastic strain analysis equipment generally consists of the following:

- A polarized source of light.
- A model made of a photoelastic material or the actual body covered in a photoelastic coating.
- A polariscope to detect the refracted or reflected light.

The projector emits polarized light onto either the actual body (Figure F-8) or a model of the actual body (Figure F-9). Models are made of a photoelastic material so the polarized light travels through the model and the refracted light travels to the analyzer. Coatings applied to the actual body consist of a layer of photoelastic material (paint or adhesive sheets) with a reflective layer underneath. The incident light is diffracted through the photoelastic layer and then reflected back through the photoelastic layer by the reflective layer.

The light traveling through the model or coating will only experience birefringence at locations of stress. The greater the stress concentration, the more the two component waves will be phase shifted.

The two diffracted components of light emerging from either the model or the coating are then bought together in a polariscope, which determines the relative phase shifts by analyzing the interference "fringe" patterns created. An example of a fringe pattern is shown in Figure F-10. Areas of high stress concentration are identified by thinner fringes, as stress concentration decreases the fringes become wider.

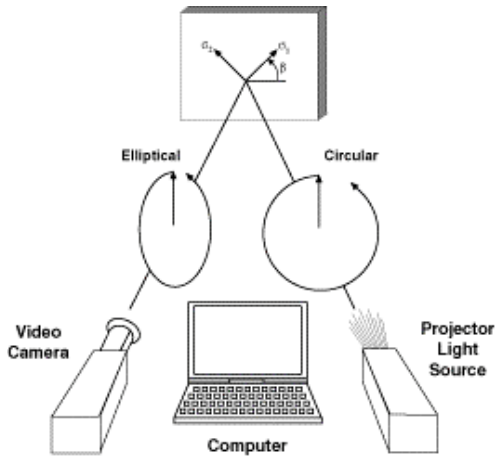


**Figure F-8. Use of a Photoelastic Coating on the Actual Body.**
**(Reprinted with permission from: Brad Boyce, VP, Stress Photonics, Inc., Madison, WI)**

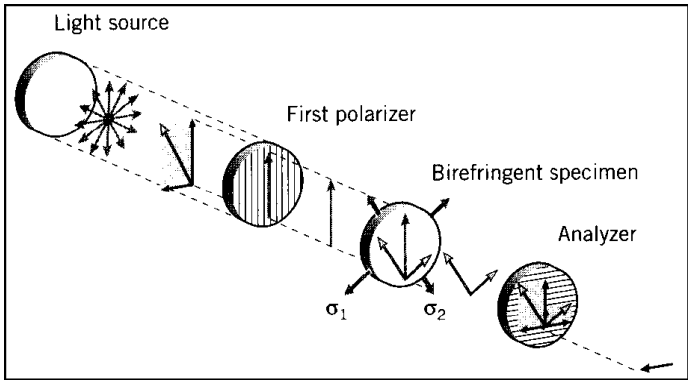


**Figure F-9. Use of a Photoelastic Model.**
**(Reprinted with permission from: D. Roylance, 2001)**

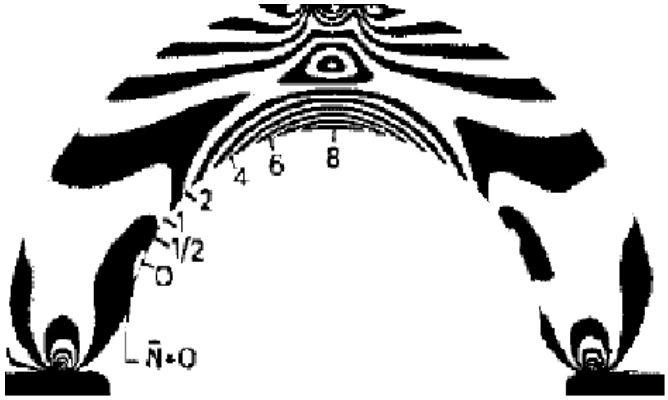


**Figure F-10. Fringe Pattern on a Centrally Loaded Arch.**
**(Reprinted with permission from: Doyle, J.F. and Phillips, J.W. , 1989)**

## F46.3 Application

Electrical resistance strain gauges are used for:

- Crack width measurement/monitoring in concrete structures.
- Small deflections in machines or structures.

Photoelastic strain gauges can be used in any components made of a homogeneous material, such as a motor shaft.

Standards which reference electrical resistance strain gauges;

- ISO 4965:1979 Axial load fatigue testing machines - Dynamic force calibration - Strain gauge technique.
- BS 6888:1988 Methods for calibration of bonded electrical resistance strain gauges.

Standards which reference photoelastic strain gauges;

- ASTM D4093-95(2005)e1 Standard Test Method for Photoelastic Measurements of Birefringence and Residual Strains in Transparent or Translucent Plastic Materials.
- ASTM C978-04 Standard Test Method for Photoelastic Determination of Residual Stress in a Transparent Glass Matrix Using a Polarizing Microscope and Optical Retardation Compensation Procedures.
- ASTM C1279-05 Standard Test Method for Non-Destructive Photoelastic Measurement of Edge and Surface Stresses in Annealed, Heat-Strengthened, and Fully Tempered Flat Glass.

## F46.4 Practical Considerations

- Variations in temperature can affect the accuracy of measurements with electrical resistance strain gauges. For instance, errors may arise due to thermal expansion of the object under analysis and also from the change in resistance of the electrical strain gauge. Errors due to temperature fluctuations can be minimized but not completely eliminated.
- A practical consideration of the photoelastic strain gauge is that either a model of the object needs to be made using a birefringent material, or the actual object needs to be coated in a photoelastic layer. This may not be feasible in many situations.

## F46.5 Advantages

- Electrical resistance strain gauge:
  - Relatively inexpensive.
  - Overall fractional errors can be less than ± 10%.
  - Possible to measure different types of strain, for example, shearing strain, poisson strain and torsional strain.

- Photoelastic strain gauge:
  - Can provide full-field displays of the strain distribution.
  - Can be applied to parts with complicated geometry and/or complicated loading conditions.
  - Sensitive and accurate.
  - Can measure residual stresses in materials.
  - Can be used to determine areas of critical stress and stress concentration factors.
  - Can measure dynamic strains.

## F46.6 Limitations

- Electrical resistance strain gauge
  - Errors due to temperature fluctuations.
  - A strain gauge only measures strain at one point. Multiple gauge arrangements are required to analyze strain along different axes and to determine bending and torsional strains.

- Photoelastic strain gauge
  - Operate best under laboratory conditions.

**Table F-48. Summary Measurement of Strain.**

| | **Electrical resistance gauge** | |
|---|---|---|
| | **Criteria** | **Assessment** |
| Technical selection | Assets covered | Crack growth monitoring of dams; civil structures |
| | Material | e.g. concrete |
| | Service area | Potable. |
| | Access requirements | No specific requirements. |
| | Limitations relating to asset condition | No specific limitations. |
| | Limitations relating to asset size/ geometry | No specific limitations. |
| | Continuous/ discrete | Continuous. |
| | Destructive/ non-destructive | Non-destructive. |
| | Interruption to supply/ function | None. |
| Technical suitability | Assessment parameters | Strain analysis. |
| | Integration with software tools | None |
| | Commercialization | Widely available. |
| | Previous/ existing use of the tool | Extensive use in the manufacturing industry. Limited use in the water industry. |
| | Ease of validation | Direct measurement. |
| | Accuracy/reliability | Quantitative |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication) | Informed engineer. |
| | Technology required (level of tool sophistication) | Strain gauges. |
| | Documentation | N/A |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | N/A |
| | Resource requirements | One or two people. |

| | **Photoelastic strain gauge** | |
|---|---|---|
| | **Criteria** | **Assessment** |
| Technical selection | Assets covered | Any components made of a homogeneous material, such as a motor shaft. |
| | Material | Potable or wastewater. |
| | Service area | Objects made of photoelastic materials can be analyzed directly. Other objects need to have a photoelastic coating applied. |
| | Access requirements | Objects are usually analyzed in a laboratory environment. |

| | Photoelastic strain gauge | |
|---|---|---|
| | **Criteria** | **Assessment** |
| | Limitations relating to asset condition | If necessary, a model made of a photoelastic material or a model with a photoelastic coating can be used to analyze strain under different loading conditions without loading the real object. |
| | Limitations relating to asset size/ geometry | No apparent limitations in principle but objects are usually analyzed in a lab. |
| | Continuous/ discrete | Continuous real time recording of fringe patterns is possible. |
| | Destructive/ non-destructive | Non-destructive. |
| | Interruption to supply/ function | Objects are usually analyzed in a laboratory environment. |
| Technical suitability | Assessment parameters | Stress and strain analysis. |
| | Integration with software tools | None |
| | Commercialization | Commercially available equipment, e.g., GFP 1200 Grey-Field Polariscope. |
| | Previous/ existing use of the tool | Extensive in the manufacturing industry.<br>Used as a quality monitoring tool in the glass industry. Limited use in the water industry. |
| | Ease of validation | Direct measurement. |
| | Accuracy/reliability | Quantitative |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication) | An informed engineer is required to perform the tests and analyze the results. |
| | Technology required (level of tool sophistication) | A polariscope and preferably the relevant software to eliminate the need for manual fringe counting. |
| | Documentation | N/A |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | Inexpensive. |
| | Resource requirements | One or two people. |

## F46.7 Bibliography


1. ISO 4965:1979 Axial load fatigue testing machines - Dynamic force calibration - Strain gauge technique
2. BS 6888:1988 Methods for calibration of bonded electrical resistance strain gauges
3. ASTM D4093-95(2005)e1 Standard Test Method for Photoelastic Measurements of Birefringence and Residual Strains in Transparent or Translucent Plastic Materials
4. ASTM C978-04 Standard Test Method for Photoelastic Determination of Residual Stress in a Transparent Glass Matrix Using a Polarizing Microscope and Optical Retardation Compensation Procedures
5. ASTM C1279-05 Standard Test Method for Non-Destructive Photoelastic Measurement of Edge and Surface Stresses in Annealed, Heat-Strengthened, and Fully Tempered Flat Glass
6. Roylance, D. *Experimental Strain Analysis,* (accessed from http://web.mit.edu/course/3/3.11/www/modules/expt.pdf), 2001
7. Doyle, J.F. and Phillips, J.W. *Manual on Experimental Stress Analysis,* 5th Edition, Society of Experimental Mechanics, Inc., 1989

## F47.0 Methylene Chloride Gelation Assessment

### F47.1 Overview

The methylene chloride (dichloromethane or methylene dichloride) test is a destructive test used to give an indication of the degree of gelation in a PVC pipe.

A short section of chamfered pipe is immersed in a bath of methylene chloride for at least 15 minutes and the chamfered surface then inspected for attack. The degree and location of attack gives an indication of the degree of gelation around the pipe circumference.

### F47.2 Main Principles

The methylene chloride test is a qualitative method used to give an indication of the level of gelation in a PVC sample. The degree of gelation is directly related to the conditions experienced by the pipe during manufacturing and so can also be used as a measure of quality assurance.

Gelation is the process by which particulate PVC is formed into a homogenous material. The degree of gelation achieved during the extrusion of a PVC pipe is related to the toughness of the material produced. A low level of gelation results in a material with reduced toughness. As such, pressure pipes made from a low level of gelation material will fail before a pipe with a high level of gelation under the same operating conditions.

Methylene chloride testing is conducted on a short length of pipe, approximately 8 inches in length. One end of this length is chamfered and that end immersed in methylene chloride for at least 15 minutes at 68°F. After this time, the length is removed and allowed to dry. After drying the chamfered end is inspected for signs of attack.

Areas of the pipe which have been attacked will become whitened or bleached. The chamfered surface will also become rough where attack has occurred. Generally there are three results from the methylene chloride test:

Type 1 – where the surface exhibits no apparent attack.

Type 2 – where the surface exhibits uniform attack.

Type 3 – where the surface exhibits non-uniform attack.

### F47.3 Application

Methylene chloride assessment is a qualitative method used to determine the gelation level of PVC pipes. The test is used to identify areas in a pipe sample with the least gelation as part of the fracture toughness testing.

- Standards which include this test are: BS 3505:1986, AS/NZS 1462.19:2006.

### F47.4 Practical considerations

- This test is widely used in industry where fracture toughness testing is conducted.
- Methylene chloride is toxic and so should be handled and stored in an appropriate fashion.
- Where quantitative measurement of gelation is required other methods are available (see DSC Gelation Assessment review).

### F47.5 Advantages

- Test gives an indication of the quality of the manufactured pipe.

## F47.6 Limitations

- When used for condition assessment, requires a pipe section to be removed for testing.
- Test solution (methylene chloride) is toxic and should be handled by trained personnel only.
- Test is broadly qualitative only.

**Table F-49. Summary Methylene Chloride Gelation Assessment.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipe assets. |
| | Material type | PVC. |
| | Service area | Potable and wastewater. |
| | Access requirements | Lab based test; requires samples to be taken. |
| | Limitations relating to asset condition | No limits due to asset condition. |
| | Limitations relating to asset size/geometry | No limitations due to sample size. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Destructive test. |
| | Interruption to supply/function | Asset must be exhumed from pipeline before testing. |
| Technical suitability | Assessment parameters | The level of gelation in a PVC sample. |
| | Integration with software tools | No integration with software tools. |
| | Commercialization of tool | Tool is a procedure |
| | Previous/existing use of the tool in sector | Test is widely used in industry. |
| | Accuracy/reliability | Test is broadly qualitative. |
| | Ease of validation of results | Results are indicative. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Operator should be trained in use of methylene chloride. |
| | Technology required (level of tool sophistication) | Test requires methylene chloride and timing device. |
| | Documentation | BS 3505:1986, AS/NZS 1462.19:2006. |
| | Availability of technical support | Test can be conducted by consultants if required. |
| Economic factors | Cost per inspection | Low cost per test. |
| | Resource requirements | Test requires a fume hood. |

## F47.7 Bibliography


1. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
2. Randall-Smith, M., Russell, A. and Oliphant, R. *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992
3. BS 3505:1986 Specification for unplasticized polyvinyl chloride (PVC-U) pressure pipes for cold potable water
4. AS/NZS 1462.19:2006 Methods of test for plastics pipes and fittings - C-ring test for fracture toughness of PVC pipes

5. ISO 9852 : 1995 Unplasticized Polyvinyl Chloride (PVCU) pipes – Dichloromethane resistance at specified temperature (DCMT) – Test method
6. Fillot, L.A Hajji, P. *UPVC Gelation level assessment Part 1: Comparison of different techniques*, Journal of Vinyl and Additive Technology, 2006

# F48.0 Motor Circuit Analysis

## F48.1 Overview

Motor circuit analysis is a non-destructive low voltage method for testing electric motor cables, connections, windings and rotors for developing faults, to reduce the likelihood of electrical failure occurring during operation. The results are not a definite indication of impending failure but need to be compared with previous tests to identify trends. The test can also indicate motor efficiency losses over time. The additional running costs could be a factor in any decision for remedial works or replacement.

## F48.2 Main Principles

When undertaking motor circuit analysis, a low voltage is applied to enable the testing of electric motor cables, connections, rotor and windings for the onset of equipment breakdown or faults. An insulation resistance test to earth is performed at either 500V or 1000V DC. The measurements which are typically undertaken when conducting motor circuit analysis include: DC resistance (R), impedance (Z), inductance (L), phase angle (Fi), multiple current/frequency response (I/F) and insulation to ground. Based on the readings obtained, the physical and electrical properties of a particular electrical component can be determined in accordance with the following guidelines.

- **Resistance (R)** is used for determining the continuity of electrical cables and connections.
- **Impedance (Z)** and **Inductance (L)** are compared to evaluate the insulation condition of winding contamination.
- **Phase angle (Fi)** and **Current/Frequency (I/F)** are used to detect winding shorts.

The above three measurements will be balanced in a fully serviceable motor. Imbalance in itself is not a definite indication of impending failure. Routine testing is required to enable trends to be generated on which failure predictions can be based. The level of imbalance before action should be fairly tolerant for non-critical motors and have a low tolerance for critical equipment.

Impedance imbalance will cause the operating temperature of the electric motor to increase placing further electro-mechanical stresses on the motor winding and rotor. Imbalances also affect efficiency as well as reliability. As the balance between phases varies, it becomes harder for the magnetic fields to turn the rotor, reducing efficiency of the motor.

## F48.3 Application

Motor circuit analysis is applicable to all types of plant that contain electrical motors and circuits.

## F48.4 Practical Considerations

- Analysis of electrical motors and circuits using motor circuit analysis is widely used throughout the manufacturing industry.

## F48.5 Advantages

- Motor circuit analysis allows for changes in electric motors and associated circuits to be trended. Action can then be taken prior to reliability being affected. Identification of efficiency loss can form part of the financial case for repair/ replacement.

- All tests are conducted using portable hand held non-specialized equipment, which enables assessment to be conducted by non electrical trained personnel. Motor circuit analysis can be conducted without the need to disassemble the motor prior to analysis.

## F48.6 Limitations

- During the assessment, the electrical motor must be electrically isolated.

**Table F-50. Summary Motor Circuit Analysis.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Electric motors. |
| | Material type | Windings. |
| | Service area | Potable and wastewater. |
| | Access requirements | Portable hand held equipment. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete readings. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Off-line. |
| Technical suitability | Assessment parameters | Electrical properties of winding. |
| | Integration with software tools | Standalone. |
| | Commercialization of tool | Fully developed and off the shelf. |
| | Previous/existing use of the tool in sector | Standard industry practice. |
| | Accuracy/reliability | High accuracy. |
| | Ease of validation of results | Can be validated by measuring separately winding resistance insulation and comparing to as installed information. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Electrician. |
| | Technology required (level of tool sophistication) | Standard computer. |
| | Documentation | Documented but no formal standard as yet. |
| | Availability of technical support | Suppliers offer service to undertake assessments. |
| Economic factors | Cost per inspection | Relatively low cost per inspection. |
| | Resource requirements | One person no more than half hour per motor. |

## F48.7 Bibliography

1. American Bureau of Shipping, *Guidance Notes on Reliability Centred Maintenance*, 16855 Northchase Drive, Houston, TX 77060 USA, July 2004, http://www.aptgroup.com.au/elec_moto.htm

## F49.0 Multi-sensor Pipe Inspection Robots

### F49.1 Overview

Pipeline inspection is undertaken in a number of sectors using "intelligent pigs" (see Intelligent Pig review) that travel with the product in the pipeline. These devices incorporate a range of inspection technologies and are effective tools for inspections undertaken over long distances, but are expensive and so their cost cannot be justified over short distances.

As an alternative, automated inspection of the inner surface of a pipe can be achieved by a mobile robot. In this approach, a robot with multiple sensors is introduced into the pipe to undertake a condition assessment using various non-destructive techniques.

The technology for these tools is still under development, but a number of systems have been produced, though not fully commercialized. The robots being developed all incorporate an array of non-destructive techniques that simultaneously assess pipeline condition. Research has also focused on the automatic interpretation of the collected data.

To date, the development of these tools has generally concentrated on assessment systems for sewers, but conceptually there is no reason why the approach could not be adopted for water mains. Nevertheless, the information provided below pertains to the inspection of sewers.

### F49.2 Main Principles

Multi-sensor robotic systems have been developed by a number of international bodies that incorporate several sensor technologies, including:

- ***Visual images***: CCTV images can be used in conjunction with other sensors such as laser profiling. Lateral connection cameras are capable of traveling up small diameter service connections (see CCTV Visual Inspection review).
- ***Acoustic monitoring techniques***: acoustic techniques can be used to assess pipe wall thickness and locate flaws in the pipe wall. Sonar uses sound to produce an image of the pipeline, which can be used to identify the pipe surface and other softer materials such as plant matter and silt (see In Pipe Acoustic Monitoring Techniques (Sonar) review).
- ***Electromagnetic***: electromagnetic techniques such as remote field eddy current, magnetic flux leakage and broad band electromagnetics can be used to assess wall thickness of metallic assets (see Remote Field Eddy Current, Broadband Electromagnetics and Magnetic Flux Leakage reviews).
- ***Ground Penetrating Radar***: ground penetrating radar can be used in-pipe to find cavities in the soil surrounding the pipe (see Ground Penetrating Radar review).
- ***Microwave sensors***: microwave backscattering sensors can be used similar to ground penetrating radar to explore anomalies in a medium range behind the pipe outer surface.
- ***Hydrochemical sensors***: hydrochemical sensors can be used to assess water quality, and for sewer pipelines can be used to indicate the presence of infiltrated groundwater.
- ***Laser profiling***: measurement of pipe diameter and deviations including ovality can be important, particularly in plastic pipes in which such deflection indicates stresses that can cause premature failure of the pipe. Laser profiling systems are available to measure pipe diameter during normal CCTV inspection.

  Examples of robot platforms include:

- The ***KARO*** and ***PIRAT*** multi-sensor robotic development projects were aimed at producing 'smart' sewer inspection vehicles equipped with several different sensor devices. The robots were connected to a mobile control and surveillance unit by a cable. One research focus of both projects was to develop methods for the automatic interpretation of sensor data to identify and characterize pipe damage. KARO, an inspection platform with exchangeable sensor modules, employed fuzzy logic to fuse and interpret data from different types of sensors. In the PIRAT project, an expert system analyzed laser images and ultrasonic data allowing classification of pipe damage.
- The ***Sewer Scanner and Evaluation Technology*** (SSET) is a flexible non-destructive evaluation data acquisition tool. At present, the prototype has a diameter of 130 mm and a length of 850 mm and weighs 25 kg. In the prototype, higher quality information on sewer condition is obtained through optical scanner and gyroscope technology. SSET records a 360° image as it travels through the pipe. This allows the pipe condition to be assessed after the inspection. This reduces the in-pipe time because the operator is not required to locate and analyze defects during the inspection itself. The interpretation system SSET implements fuzzy set theory and fuzzy logic techniques to automatically identify, classify and rate pipe defects.
- ***SAM*** an interdisciplinary German research and development project on "Sewer Defect Characterization by Multisensor Systems" involves the development and linkage of different sensor systems. SAM includes a commercial CCTV system as well as a number of sensors, including, microwave backscattering, hydro chemical, acoustic impact, optical triangulation, geophysical and radioactive probes. The interpretation system of SAM also implements fuzzy set theory and fuzzy logic techniques to automatically identify, classify and rate pipe defects.
- The ***MAKRO*** robot is an autonomous sewer robot and its frame is flexible both horizontally and vertically. The robot is equipped with a set of internal sensors, which serve mainly to determine the robot's relative and absolute position within the pipe. The robot's external sensors enable analysis of its environment and include obstacle detection, collision avoidance, motion control, and landmark detection - a subtask of self-localization.
- ***Pipe Rover*** is currently being developed in Hong Kong for assessment of pipes over one meter in diameter. It is an underwater robot for inspection of water ducts, pipes and foul water drains. It is especially suitable for offshore sewer outlets or power station outfalls, where the pipes may terminate kilometres offshore and run deep in water. Pipe Rover has two propulsion mechanisms. For flat-bottomed ducts with few obstructions; tracks propel the robot, while for pipes, legs are used. The sensors include a color video inspection camera with pan, tilt and lights, ultrasonic obstacle detection and distance/depth/temperature/heading/pitch and roll information.

## F49.3 Application

Intelligent inspection of sewer pipelines using multiple sensor robots to simultaneously obtain a wide range of condition data.

## F49.4 Practical considerations

- Multi sensor systems are generally still in the development stage, and as such these systems are not widely used. Nevertheless, various platforms have been subject to field tests:

- SSET was introduced to North American market in 1997; field trials covered 38.5 kms (126,612 ft) of sewer inspection in 13 participant cities. More recently, a 5.7km (19,000 ft) sewer evaluation project for City of Atlanta and a project for Eastman Chemical Company, Tennessee, have been completed.
- PIRAT has been tested in 5 km of sewers in Melbourne.
- SAM is currently being field-tested in several German cities.

- The evaluation of SSET is on-going. Work on KARO has stopped, though parts of it are integrated into a new project SAM. PIRAT is unlikely to be commercialized.
- The external sensors available on MAKRO at the moment are very limited and considerable development is still needed in this area before it would be usable for automated pipeline inspection.

## F49.5 Advantages

- Robots can be used to simultaneously gather large amounts of useful information about a pipeline.
- Tools can be customized to gather data of specific interest for each asset type.

## F49.6 Limitations

- The capital cost of inspections systems can be high due to the sensors incorporated in them.
- Robots are not yet commercially available.

**Table F-51. Summary Multi-sensor Pipe Inspection Robots.**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Pipe assets. |
| | Material type | Any. |
| | Service area | Mainly wastewater. |
| | Access requirements | Access to interior of pipe for inspection probe (robot). |
| | Limitations relating to asset condition | Blocked and clogged assets cannot be inspected past blockages. |
| | Limitations relating to asset size/geometry | Depends on equipment but minimum diameter of around 150mm. |
| | Continuous/discrete | Continuous. |
| | Destructive/non destructive | Non-destructive test. |
| | Interruption to supply/function | Depends on sensors being used. |
| Technical suitability | Assessment parameters | Depends on sensors being used. |
| | Integration with software tools | Fully integrated software for analysis of data. |
| | Commercialization of tool | Systems are either still in development or have been abandoned. |
| | Previous/existing use of the tool in sector | Limited testing for development purposes. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Depends on sensors being used. |
| Utility technical capacity | Asset management sophistication required | Associated with high levels of asset management sophistication. |
| | Skills required (level of tool sophistication); usability | Training in use of specific device and associated sensors is required. |
| | Technology required (level of tool sophistication) | Highly sophisticated. |

| | Criteria | Assessment |
|---|---|---|
| | Documentation | Use and development documented in the literature. |
| | Availability of technical support | Limited. |
| Economic factors | Cost per inspection | High at present. |
| | Resource requirements | Robot and team to operate device. |

## F49.7 Bibliography


1. Burn, L.S., Eiswirth, M., DeSilva D. and Davis P., *Condition Monitoring and its Role in Asset Planning*, Pipes Wagga Wagga 2001, Charles Sturt University, Wagga Wagga, N.S.W, 2001
2. Ratliff, A. *An overview of current and developing technologies for pipe condition assessment*, Pipelines 2003, ASCE 2004

# F50.0 Oil Testing

## F50.1 Overview

In many different types of equipment, oil is either used as a lubricant to reduce the rate of wear and deterioration of internal moving components (e.g., in an air compressor, gearbox, diesel/petrol engines), or used as a cooling medium to transfer heat (e.g., from the core and coils contained in an electrical transformer).

Routine assessment of a sample of oil is a non-destructive method that can be used to give an indication of the current condition of the plant. A number of tests are conducted on the oil sample that can identify component wear, fatigue and corrosion. The analysis can also give an indication of oil contamination and deterioration, which can indicate when oil should be changed.

## F50.2 Main Principles

### F50.2.1 Oil as a Lubricant

In many different types of equipment (petrol/diesel motors, gearboxes, compressors and hydraulic systems), analysis of the lubricating oil for the presence of sediment particles, corrosion, fatigue and changes in the properties of the oil (such as density and viscosity) can often provide an indication of the equipment's current state of operation and internal condition.

Over time the level of oil and the changes in the oil properties have an influence on the rate of wear and deterioration of moving internal components, with the formation of ferrous particles in the lubricating oil providing an indication of the rate of wear of internal plant components.

The following laboratory-based assessments are typically undertaken on a routine basis to gain an indication of the condition of equipment through analysis of its lubricating oil.

- **Ferrographic analysis** is a technique that can be used to determine the density and size of particles that have formed in the lubricating oil as a direct result of wear, fatigue and/or corrosion. A sample taken from the equipment is analyzed by diluting the sample in a fixer solvent that is then passed over a glass slide subjected to a magnetic field. The applied magnetic field results in the separation of the ferrous particles from the non-ferrous particles. The density of the particles and the ratio of the large to small particles indicate the type and the extent of the wear that is occurring to internal components.
- **Particle counter analysis** is a method undertaken to monitor particles in lubricating and hydraulic oils caused by corrosion, wear and contamination. The two most common methods used for particle counting are light extinction and light scattering. In the light extinction method, an incandescent light is used to shine on a cell that the oil sample moves through under controlled flow and volume conditions. A particle counter measures the light that passes through the sample to determine the number of particles in a predetermined size range. In the light scattering assessment technique, a laser is used to shine light through an object cell that the oil sample fluid moves through under controlled flow and volume. As opaque particles pass through the laser, the scattered light created is measured and translated into a particle count.
- **Atomic emissions spectroscopy** can be used to determine the presence of corrosion and wear products, contaminants and additives in hydraulic and lubricating oils. The characteristic radiation emitted when samples are subjected to high energy and temperature are measured to determine the presence of elements such as iron,

aluminum, chromium, copper, lead, tin, nickel and also components of oil additives such as boron, zinc, phosphorus and calcium.

- **Kinematic viscosity** assessment provides an indication of the deterioration of oil over time as well as an indication of the contamination of the oil by fuel and other oils. During the assessment, the oil's resistance to flow under controlled pressure and temperature is measured by forcing a sample to flow through a capillary viscometer. The viscosity of the oil can be determined from the results obtained.

### F50.2.2 Oil as a Heat Transfer/Insulating Medium

In transformers, oil is used primarily as a cooling medium to transfer heat from the core and coils to the external radiator banks, while also forming part of the insulation system. Oil filled transformers have the core and coil assembly placed in a tank filled with dielectric cooling oil. The primary insulation system used in an oil-filled transformer is Kraft paper, wood, porcelain and oil. In more modern transformers, paper that is chemically treated to improve its tensile strength properties and resistance to decay caused by immersion in oil are commonly used.

Over time, the insulating properties of the oil may deteriorate as a result of contamination and the formation of moisture leading to transformer break down. In order to determine the condition of the oil and the electrical insulating properties to reduce the likely hood of transformer break down, the following laboratory based oil tests are commonly undertaken.

- **Sediment tests (ASTM D – 1698)**, to determine the properties of sediment that has formed in the oil due to contamination and or deterioration over time. The analysis involves taking a sample of the oil and using a centrifuge to separate the sediment from the oil to enable assessment of the sediment properties.
- **Karl Fisher titration test (ASTM D – 1744)**, can be used to determine the amount of moisture in an oil sample by measuring the electrical current flow between two electrodes immersed in the sample solution with the result reported as the amount of water in parts per million.
- **Dielectric strength tests** are used to measure the insulating properties of electrical insulating oils. The electrical insulating properties of oil can change due to the deterioration as a result of contamination or oil breakdown. The test is conducted by subjecting the sample to an electrical stress at a given temperature by passing a voltage through the sample.

In addition to the laboratory assessments outlined above, a visual inspection conducted at six monthly intervals of the transformer dehydrating breather silica gel crystals can also be undertaken, to ensure the color of the crystals has not changed. If on inspection more than 50% of the crystals have changed color, replacement is recommended due to the possibility of moisture entering the unit during warming up/cooling down cycles and resulting in premature insulation failure of the oil. Insulating oil decay is found to be the single greatest cause of power transformer failure.

## F50.3 Application

Oil testing methods are used to assess the properties of oil and can be used to determine the condition of internal moving components in petrol/diesel engines, gearboxes and transmissions, and also those types of plant that use oil as a heat transfer medium, such as electrical transformers, to provide a effective method of determining the current condition and rate of deterioration of plant equipment.

- ASTM D – 1698, ASTM D – 1744 and ISO/DIS 18436-4 reference different oil testing methods.

## F50.4 Practical Considerations

- The majority of the assessments used in determining the type of contaminants and particles present in oil samples are laboratory based assessments, and as a result require trained technical staff to undertake these assessments and interpret test results.

## F50.5 Advantages

- Oil testing can be undertaken as a part of a routine maintenance program to provide a means of obtaining an early indication of plant failure.
- Oil testing can be used to optimize the frequency of oil changes in plant equipment, preventing premature oil changes and indicating when an oil change is due.

## F50.6 Limitations

- The majority of the assessments used in determining the type of contaminants and particles present in oil samples are laboratory based assessments, and as a result require trained technical staff to undertake these assessments and interpret test results.

**Table F-52. Summary Oil Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Wastewater/water infrastructure transformers, oil switchgear, mechanical components requiring oil as lubricant. |
| | Material type | Electrical insulant/cooling medium, mechanical lubricant. |
| | Service area | Potable and wastewater. |
| | Access requirements | Sample of oil required to be taken. Transformers usually have tap points, switch gear requires removal from housing. Mechanical some have sample taps. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete reading. |
| | Destructive/non destructive | Non destructive. |
| | Interruption to supply/function | Transformers on-line. HV gear off-line. Mechanical dependent on equipment |
| Technical suitability | Assessment parameters | Impurities and dielectric strength of oil. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Fully commercially available. |
| | Previous/existing use of the tool in sector | Standard industry practice. |
| | Accuracy/reliability | Accurate results of sample but with electrical equipment are indicative of condition. |
| | Ease of validation of results | Indicative requiring visual inspection. |
| Utility technical capacity | Asset management sophistication required | Generic approach. Is commercially available. |
| | Skills required (level of tool sophistication); usability | Skilled operator for dielectric strength. Laboratory for analysis |
| | Technology required (level of tool sophistication) | Specialist equipment for dielectric strength. Laboratory equipment for analysis. |
| | Documentation | Method is widely used and documented. ISO/DIS 18436-4. |
| | Availability of technical support | Many laboratories available. |
| Economic factors | Cost per inspection | Depends on tests. |
| | Resource requirements | One man sample. Offsite laboratory. |

## F50.7 Bibliography


1. American Bureau of Shipping, *Guidance notes on Reliability Centred Maintenance*, 16855 Northchase Drive, Houston, TX 77060 USA, July 2004
2. ASTM D – 1698, Standard test method for sediment and soluble sludge in service aged insulating oils
3. ASTM D – 1744, Standard test method for determination of water in liquid petroleum products by Karl Fischer reagents
4. ISO/DIS 18436-4: Condition monitoring and diagnostics of machines - Requirements for training and certification of personnel - Part 4: Field lubricant analysis. *This document is a Draft International Standard*

# F51.0 On-Line Leak Detection Systems

## F51.1 Overview

In the oil and gas sector it is common to have on-line leak detection systems for real time monitoring of transmission pipelines. All such systems have the same underlying principle; continuous on-line monitoring of flow parameters (flow and/or pressure) at the upstream and downstream ends of a pipeline is used to determine if there are any hydraulic anomalies.

Approaches range from simple comparison of "metered out" volumes with "metered in" volumes, the monitoring of 'rate of change' in parameters of interest, and complex computational pipeline monitoring.

Computational Pipeline Monitoring (CPM) uses an algorithmic approach to detect hydraulic anomalies in pipeline operating parameters. The data from sensors is fed into a computer model that can indicate if there is a new leak within the sensitivity of the algorithm. The CPM system then provides an alarm and displays other related data to the pipeline controllers to aid in decision-making.

## F51.2 Main Principles

Continuous on-line monitoring of flow and pressure is carried out at the upstream and downstream ends of a pipeline. The simplest approaches compare "metered out" volumes with "metered in" volumes. Other relatively straight forward approaches look at the rate of change in monitored parameters; operating parameters are monitored at various points along the pipeline and the system reacts when there is a change at an abnormal rate.

More complex approaches utilize complex computational monitoring systems that simultaneously monitor numerous operating conditions. Flow, pressure and other data are fed into a mathematical model of the pipeline. The system then continuously compares the measured values with the values predicted by the model. A discrepancy between measured and predicted value indicates a change in the operating characteristics of the pipeline; for example, the presence of a new leak or other hydraulic anomaly.

## F51.3 Application

Used as a technique for leak detection in the oil and gas industry by pipeline operators to protect the public and the environment from consequences of a pipeline failure. There is the potential to expand use into the water industry for the monitoring of transmission pipes.

## F51.4 Practical considerations

- This approach to on-line leak detection is commonly adopted in the oil and gas sector. The technique relies upon relatively frequent monitoring of at least one flow and one pressure at opposite ends of the pipeline. A potential difficulty in applying this technique to the water sector is that pipeline flow needs to be monitored to high degree of accuracy, which is currently not standard practice.
- With an algorithmic approach to detect hydraulic anomalies, the technique can only indicate the presence of a new leak; any leak existing when the model was first calibrated will form part of the steady state conditions. A significant leak can, however, be indicted by the difficulty in making the model fit or in a discrepancy between the flow into and out of the pipeline.

- Operational transients such as pump starts, line fills, valve closures, etc., may be modeled as well, so that this automatic leak detection system can continue to work during operational changes that occur in the normal day-to-day operation of the pipeline system.

## F51.5 Advantages

- Provides real time assessment of structural condition through detection of new leaks.

## F51.6 Limitations

- Cost could be prohibitive in the water sector except where there are specific risk and revenue drivers.

**Table F-53. Summary On-Line Leak Detection Systems.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Water pipelines. |
| | Material type | N/A |
| | Service area | Potable. |
| | Access requirements | None, on-line monitoring technique. |
| | Limitations relating to asset condition | Applicable to structurally sound assets. |
| | Limitations relating to asset size/geometry | None, though only cost-effective for large mains. |
| | Continuous/discrete | Continuous readings. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Asset remains on-line. |
| Technical suitability | Assessment parameters | Change in flow parameters that indicate a leak. |
| | Integration with software tools | By definition, integrated software tool. |
| | Commercialization of tool | Developed for the oil and gas sector. |
| | Previous/existing use of the tool in sector | No uptake in the water sector. |
| | Accuracy/reliability | Quantitative assessment. |
| | Ease of validation of results | Difficult to validate except by locating new leak. |
| Utility technical capacity | Asset management sophistication required | Would require a high degree of sophistication to justify. |
| | Skills required (level of tool sophistication); usability | Automated monitoring. |
| | Technology required (level of tool sophistication) | High level of instrumentation; sophisticated tools. |
| | Documentation | N/A |
| | Availability of technical support | N/A |

## F52.0 PARMS-Planning

### F52.1 Overview

The Pipeline Asset and Risk Management System (PARMS) is a suite of computer-based models developed by CSIRO, designed to assist in the management of water supply network assets. Two tools have been commercialized to date; PARMS-Planning and PARMS-Priority. PARMS-Planning is designed to be used annually for long-term planning and regulatory reporting, whereas PARMS-Priority is designed to be used on a regular basis to allow determination of which assets to rehabilitate to meet the water utility's strategies (see PARMS-Priority review).

PARMS-Planning is a software tool that allows assessment of both short and long-term repair and replacement strategies for water pipelines. The PARMS-Planning software can be used to:

1. Forecast the expected annual number of failures.
2. Assess replacement based upon the predicted number of failures in any one year.
3. Calculate the cost implications of different management and operational scenarios.

PARMS-Planning assesses replacement needs based upon the predicted number of pipe failures, in conjunction with the policy adopted by the water utility. The failure rates of each pipe are estimated for each year in the forecast period. The product of the failure rate and the length of the pipe give the number of failures for that pipe asset. The total number of failures in the system in any one-year is given by the aggregate of failures for individual assets.

### F52.2 Main Principles

The overall approach used by PARMS-Planning is to forecast the expected annual number of failures for each individual pipe asset over the long term (the next 30 to 100 years), based on various determinants including the age of each asset, its installation and operating conditions, and its failure history. The calculation process for each year involves the following:

- Estimating the expected number of failures of each pipe for each of the years in the forecast period using a relevant statistical or physical probabilistic failure model. This expected number is then converted into an integer number of failures using a negative binomial probability distribution.
- Estimating the cost of each failure. This involves modeling whether the failure was repaired by clamping; how long the interruption was and when it started; and consequentially what rebates and penalties applied (where regulators require such payment); and whether neighboring pipes also experienced an interruption.
- Evaluating (in conjunction with a set of policy options) which pipes should be considered for replacement. Pipes that are identified as replacement candidates are then either replaced or considered for shut-off valve insertion (inserting a valve to reduce the number of customers impacted by a pipe failure). The cost of the selected option is accumulated.

The costs of maintenance are provided within PARMS-Planning per repair, and the cost of replacement assets are calculated from costs per unit length. Replacements reduce the length of existing assets and create a new asset in the year of replacement.

The chosen policy options determine when a pipe is a candidate for replacement. This can be on the basis of the number of failures experienced by the pipe, the number of unplanned

interruptions, or the net present value of the future costs of the alternatives of maintenance or replacement.

As noted, the analysis can be tailored to the strategy/policy of individual utilities, but in general those assets that have multiple failures in any one-year are targeted for replacement (the number of allowable failures per year depending upon customer preference).

## F52.3 Application

PARMS-Planning is used to undertake long term strategic planning for water distribution networks and model the impact that management strategies will have on performance.

## F52.4 Practical considerations

- PARMS-Planning is a commercial software package that has been implemented in several authorities in Australia. It is a Windows based application with an easy to use GUI.
- PARMS-Planning requires failure curves to be developed through the analysis of the utility's data. These curves are utilized in the forecasting of network performance and provide the basis for the management modeling scenarios. Generic failure curves are currently being developed by CSIRO.
- Users of the software have reported that it has enabled them to better understand the long term implications of their management strategies and has provided insight into how their networks are actually performing.

## F52.5 Advantages

- The expected failure rate over time can be described for every individual asset in the network.
- PARMS-Planning is able to assess replacement based upon the predicted number of failures in any one year, and thus is able to include customer preferences for supply interruptions.
- The software allows the modeling of modified asset management strategies that might occur as a result of regulatory changes or business objective changes.
- A combination of graphical and tabular outputs provides users with a detailed breakdown of network performance by pipe material, pipe age, failure type, etc.
- The system incorporates a simple GIS interface that allows network information to be displayed in an incorporated GIS viewer.

## F52.6 Limitations

- PARMS-Planning requires good quality asset data as well as failure history data in order to develop the failure curves.
- The failure curve development is normally undertaken by consultants and is an additional cost to the software package.

**Table F-54. Summary PARMS Planning.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, water pipeline infrastructure. |
| | Granularity | System and asset level. |
| | Service area | Potable |
| Technical suitability | Focus of analysis | Long term asset management planning using asset failure curves developed from utility asset data. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good asset data is available; a 'light' version is currently in development that could be more suited to small utilities. |
| | Commercialization | Commercial software. |
| | Previous/existing use of the tool | Used by several large utilities in Australia . |
| | Ease of validation | Initial validation is provided in statistical analysis of failure data and development of failure curves. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Potable only. Subsystem to system level. |
| | Integration with other tools/GIS | Integrates with most database systems and requires standard GIS shape files for GIS implementation. |
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management where good asset data is available. |
| | In-house skills required | Asset manager/engineer. |
| | Technology required | PC based tool. Windows based operating system. |
| | Documentation | Research and development fully documented. |
| | Data Requirements | Good quality asset data and asset failure history data is required. |
| | Linking to asset data | Linking to utility asset database is provided in initial setup. |
| | Availability of software and technical support | Software available through CSIRO, as is technical support. |
| | Usability | Simple user interface, once data is loaded. |

## F52.7 Bibliography


1. Burn, L. S., Tucker, S. N., Rahilly, M., Davis, P., Jarrett, R., and Po, M. *Asset planning for water reticulation systems - the PARMS model*. Water Science and Technology: Water Supply, 3(1-2), 55-62, 2003
2. Burn, S., Ambrose, M. D., Moglia, M., and Tjandraatmadja, G. *PARMS - An approach to strategic management for urban water infrastructure*. IWA Leading edge conference on strategic asset management. San Francisco, 26-27 July, 2004
3. Burn, S., Ambrose, M. D., Moglia, M., Tjandraatmadja, G., and Buckland, P. *Management strategies for urban water infrastructure*. IWA World Water Congress. Marrakech, Morocco, October, 2004

## F53.0 PARMS-Priority

### F53.1 Overview

The Pipeline Asset and Risk Management System (PARMS) is a suite of computer-based models developed by CSIRO, designed to assist in the management of water supply network assets. Two tools have been commercialized to date; PARMS-Planning and PARMS-Priority. PARMS-Planning is designed to be used annually for long-term planning and regulatory reporting (see PARMS-Planning review), whereas PARMS-Priority is designed to be used on a regular basis to allow determination of which assets to rehabilitate to meet the water utility's strategies.

PARMS-Priority is a software tool that assists water authorities to make tactical renewal and valve insertion decisions for water distribution pipes and networks. The PARMS-Priority software can be used to:

- Prioritize between pipe assets targeted for potential renewal.
- Develop work packages for effective programming of pipe replacement.
- Evaluate pressure reduction scenarios.
- Analyze shut-off block reduction scenarios (inserting valves to reduce the number of customers impacted by a failure).
- Facilitate information management of water pipe asset and failure information.
- Predict pipeline failures and costs for individual assets; including service levels.

### F53.2 Main Principles

PARMS-Priority is designed to compliment PARMS-Planning by allowing water utilities to spend available renewal budgets in an efficient manner by supporting the renewals prioritization process. The analysis undertaken within PARMS-Priority is based on estimating risk; risks involved with different scenarios and options are assessed using a standard risk management approach, as per Australia/New Zealand standards. Risk is calculated by combining the output of failure prediction models with the output of cost assessment models.

The failure forecasting is developed from a utility's failure database using statistical analysis. Depending upon pipe material, failure predictions are based on either statistical Non-Homogeneous Poisson models or physical probabilistic models. The predictions provide failure rates and probabilities for each pipe in the network, taking into consideration the age of the pipe, material type and diameter, operating pressure, length of pipe, the pipe's failure history and where possible soil. The costs and consequences of failures are related to repairs, customer supply interruptions – rebates, penalties and customer preferences, as well as flooding and damages.

Costs and failure rates and probabilities are combined to associate risk values with different scenarios relating to pipeline renewal, pressure reduction and valve insertions. Scenarios are ranked on various risk and financial indicators such as net-present value of savings/losses, and payback period.

### F53.3 Application

PARMS-Priority is used to prioritize a water pipe renewal program by targeting high risk assets.

## F53.4 Practical considerations

- PARMS-Priority is a commercial software package that has been used in several authorities in Australia. It is a Windows based application with an easy to use GUI.
- As with PARMS-Planning, PARMS-Priority requires failure curves to be developed through the analysis of the utility's data. These curves are utilized in the forecasting of network performance and provide the basis for the management modeling scenarios. Generic failure curves are currently being developed by CSIRO.

## F53.5 Advantages

- Failure predictions are based on rigorous analysis of the failure history of pipe groups.
- PARMS-Priority supports the user in identifying renewal clusters, and evaluating the effects of pressure reduction and valve insertions.
- The risk calculation engine can be used to investigate user-specified scenarios and to prioritize between different actions, which allows for proactive asset management.
- A query engine allows authorities to target specific areas of their network to review performance. A combination of graphical and tabular outputs provides users with a detailed breakdown of asset performance by pipe material, pipe age, failure type, etc.
- The system also incorporates a simple GIS interface that allows asset information to be displayed in an incorporated GIS viewer.

## F53.6 Limitations

- PARMS Priority requires good quality asset data to be available as well as failure history data in order to develop the failure curves.
- The failure curve development is normally undertaken by expert consultants and is an additional cost to the software package.

**Table F-55. Summary PARMS-Priority.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Pipes, water pipeline infrastructure. |
| | Granularity | System, sub-system and Asset level. |
| | Service area | Potable. |
| Technical suitability | Focus of analysis | Decision support system to assist water authorities make renewal and valve insertion decisions for water distribution pipes. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good asset data is available. |
| | Commercialization | Commercial software. |
| | Previous/existing use of the tool | Used by several large utility in Australia. |
| | Ease of validation | Initial validation is provided in statistical analysis of failure data and development of failure curves. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Potable only; asset to system level. |
| | Integration with other tools/GIS | Integrates with most database systems and requires standard GIS shape files for GIS implementation. |

| | Criteria | Assessment |
|---|---|---|
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management where good asset data is available. |
| | In-house skills required | Asset manager/engineer. |
| | Technology required | PC based tool. Windows based operating system. |
| | Documentation | Users standard asset classification system as developed by WSSA Australia, but can be tailored to other regional standards. |
| | Data Requirements | Good quality asset data and asset failure history data is required. |
| | Linking to asset data | Linking to utility asset database is provided in initial setup. |
| | Availability of software and technical support | Software available through CSIRO, as is technical support. |
| | Usability | Simple user interface, once data is loaded. |

## F53.7 Bibliography

1. Moglia, M., Burn, S., Meddings, S. *Decision support system for water pipeline renewal prioritisation*, ITcon Vol. 11, pp 237 – 256, 2006

## F54.0 Passive Acoustic Inspection of Pipes (Acoustic Emission)

### F54.1 Overview

This technique is a non-destructive method used to detect the release of sound energy when wires in pre-stressed concrete pipes fail.

During the manufacture of pre-stressed concrete pipes (also known as pre-stressed cylinder concrete pipe or PCCPs) high strength steel cables (bundles of steel wires) are wrapped under tension around a central core to apply a compressive stress to the concrete. As the pipe degrades, the steel cables corrode. Eventually, wires will break releasing the stored energy, the majority of which is released as sound. This sound propagates along the pipe via the pipe wall and the water within the pipe.

As deterioration continues, the prestressing cable will continue to corrode and wires will break releasing more energy in a series of discrete events; these can be detected by hydrophones or other sensors.

### F54.2 Main Principles

Passive acoustic inspection uses acoustic sensors, hydrophones or accelerometers to detect failures occurring in the prestressing wire of pre-stressed concrete pipes. To locate these pipe sections, the sensors are placed along the pipeline while the pipe is in service to log when a wire fails. The location of a failure is determined by using data from the sensors on either side of the failure. The time difference between the sound reaching the two sensors, the speed of sound in water, and the distance between the sensors is used to locate where the failure occurred.

Acoustic sensors can be located in assets on a temporary basis or as a permanent means of pipeline monitoring.

### F54.3 Application

Passive acoustic inspection is used to locate actively deteriorating sections of pre-stressed concrete pipe.

### F54.4 Practical considerations

- The monitoring technique is fully commercialized and used to manage the risk associated with the catastrophic failure of pre-stressed concrete pipes.
- The sensor spacing is limited by the presence of discontinuities in the pipeline between the failure and the sensors, such as valves or elbows.
- Sensor spacing can range from 300 ft to 1500 ft based on the pipeline diameter and presence of discontinuities.
- Inspections are generally used on pipes greater that 30” diameter.
- Hydrophones are inserted into the water column through a minimum of a ¾’’ tap. Accelerometers are installed directly on the pipe surface. Both sensors can be installed when the pipeline is in service.

### F54.5 Advantages

- Actively deteriorating sections of pipe can be located without exhuming the pipe or removing it from service; the rate of deterioration can be determined to prioritize replacement.

- Sensors can be left in place as a permanent means of monitoring asset condition.
- Technique can also detect sounds produces during cracking of the concrete.
- Inspection is not limited by heavy walled PCCP.
- Manhole access is not required.

## F54.6 Limitations

- Accuracy of section location is affected by discontinuities in the pipeline between the failure and the hydrophones.
- This technique does not quantify the amount of broken wires in the pipe.

**Table F-56. Summary Passive Acoustic Inspection of Pipes (Acoustic Emission).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes. |
| | Material type | Pre-stressed concrete. |
| | Service Area | Potable and wastewater. |
| | Access requirements | ¾" access required for entry of hydrophone into water column or exposed pipe surface for accelerometer. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | Generally used for 30"diameter and above. |
| | Continuous/discrete | Continuous. |
| | Destructive/non destructive | Non-destructive test. |
| | Interruption to supply/function | Inspection requires pipe to be on-line. |
| Technical suitability | Assessment parameters | Location and number of wire related events during the monitoring period. |
| | Integration with software tools | Can be telemetered. |
| | Commercialization of tool | Tool is available from several commercial suppliers. |
| | Previous/existing use of the tool in sector | Wide use in North America. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Results can be validated by exposing a pipe section for visual inspection and/or performing a RFEC/TC inspection. |
| Utility technical capacity | Asset management sophistication required | Generic approach |
| | Skills required (level of tool sophistication); usability | Training in use of equipment is required. Analysis of results conducted by experts. |
| | Technology required (level of tool sophistication) | Specialized equipment is used, can be obtained from supplier or testing can be conducted by contractors. |
| | Documentation | Use documented in the literature. |
| | Availability of technical support | Tool support available from supplier. |
| Economic factors | Cost per inspection | Pipeline specific. |
| | Resource requirements | Units are battery powered. |

## F54.7 Bibliography


1. *The pressure pipe inspection company homepage*, http://www.ppic.com/services/aet.asp, accessed 2006
2. Dingus, M., Haven, J. and Austin, R. *Nondestructive None Invasive Assessment of Underground Pipes*, AwwaRF, USA, 2002
3. Makar, J. M. ; Chagnon, N. *Inspecting systems for leaks, pits, and corrosion*, National Research Council of Canada, Institute for Research in Construction, NRCC-42802 (downloaded from www.nrc.ca/irc/ircpubs), 1999

# F55.0 Performance Testing of Rotating Machinery

## F55.1 Overview

Performance testing of rotating machinery is a non-destructive method used to assess whether equipment is operating as per the original specification or manufacturer's data.

Performance tests are usually conducted in the manufacturer's shop as part of 'factory acceptance testing' and again on-site as part of 'site acceptance testing'. Ideally performance tests should also be carried out periodically to ensure that equipment continues to operate satisfactorily. Periodic performance tests can reveal deterioration and inefficiencies in equipment that can lead to significant savings on power bills and maintenance costs.

## F55.2 Principles

To undertake a performance test, a rotating machine needs to be run under a range of operating conditions. For example, the shaft speed or applied load can be altered to give a range of test results. For each operating condition, data needs to be collected that can be used to calculate parameters such as efficiency and load capacity. The data collected and parameters calculated will depend on the particular type of rotating machinery under analysis. The test results are compared to the specification or manufacturer's data to determine if the equipment is operating as required.

Performance testing of pumps is particularly common. For on-site pump testing, a range of flow conditions can be tested by adjusting the position of a downstream valve to alter the pump delivery head. Upstream and downstream calibrated pressure gages and a flow meter are required for this testing. Typically, the flow rate, suction head, delivery head and motor's current are measured. The results can be plotted on top of the manufacturer's pump curves to show the difference between the actual operating performance and the design (or optimal) operating performance. The manufacturer will typically guarantee that a pump will operate within a particular range of the pump curve. Performance testing of pumps can help diagnose pump problems such as cavitation, impeller damage and case damage. Noise, temperature and vibrations may also be measured as part of the pump performance test.

## F55.3 Application

Performance testing is applicable to all rotating machinery. Applications for the water and wastewater industry include pumps, fans, motors, screw conveyors, air blowers, compressors, mixers and centrifuges.

- ANSI/HI 1.6-2000 Centrifugal Pump Tests.
- ANSI/HI 2.6-2000 Vertical Pump Tests.
- ANSI/HI 12.1-12.6 (A128) Rotodynamic (Centrifugal) Slurry Pump Standard.
- ISO 9906:1999 Rotodynamic pumps - Hydraulic performance acceptance tests - Grades 1 and 2.
- ISO 13380:2002 Condition monitoring and diagnostics of machines - General guidelines on using performance parameters.

## F55.4 Practical Considerations

- In order to undertake a performance test the rotating machinery needs to be operated under a full range of operating conditions.

## F55.5 Advantages

- The performance of equipment can degrade significantly with time. Performance testing can highlight inefficiencies and the need for the repair or replacement of components, which can lead to cost savings.

## F55.6 Limitations

- On-site performance tests can be limited by the equipment available to take measurements. For example, a pump performance test is limited by the location of the pressure gauge. If a pressure gauge cannot be located close to the pump then the measurement will be affected by friction head losses in the pipe and fittings giving unreliable results.

**Table F-57. Summary Performance Testing of Rotating Machinery.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Pumps, fans, motors, screw conveyors, air blowers, compressors, mixers and centrifuges. |
| | Material type | N/A |
| | Service area | Potable and wastewater. |
| | Access requirements | None. |
| | Limitations relating to asset condition | It may be decided that equipment in poor condition should not be exposed to the full range of operating loads and conditions. |
| | Limitations relating to asset size/geometry | N/A |
| | Continuous/discrete | Continuous readings over test duration. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | On-line. |
| Technical suitability | Assessment parameters | The performance of rotating machinery, e.g., efficiency, head, pressure, noise, vibration. |
| | Integration with software tools | It is possible to use SCADA software to record the measured data. |
| | Commercialization of tool | Tool is fully developed. |
| | Previous/existing use of the tool in sector | Widespread use throughout the water and other sectors. |
| | Accuracy/reliability | Dependent on the accuracy of the measuring devices, e.g., flow meters, manometers. |
| | Ease of validation of results | Validation by repetition. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | The operator needs to be able to interpret the data collected. For instance, they should be able to read pump curves. |
| | Technology required (level of tool sophistication) | Only basic measurement devices are required. SCADA may be used to track the results but is not required. |
| | Documentation | ANSI/HI 1.6-2000, ANSI/HI 2.6-2000, ISO 9906:1999, ISO 13380:2002. |
| | Availability of technical support | Technical support is available from manufacturers. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. |

## F55.7 Bibliography


1. ANSI/HI 1.6 (M104) American National Standard for Centrifugal and Regenerative Turbine Pump Tests
2. ANSI/HI 2.6 (M108) Vertical Pump Tests
3. ISO 9906:1999 Rotodynamic pumps - Hydraulic performance acceptance tests - Grades 1 and 2.
4. ISO 13380:2002 Condition monitoring and diagnostics of machines - General guidelines on using performance parameters
5. ANSI/HI 12.1-12.6 (A128) Rotodynamic (Centrifugal) Slurry Pump Standard

## F56.0 Phenolphthalein Indicator (Carbonation Testing)

### F56.1 Overview

The phenolphthalein indicator test is a quick method used to indicate the presence of free lime in cementituous materials.

Samples are removed from the structure being tested, such as a pipe section, and stained with the indicator. Areas with low or no free lime content remain colorless, while areas with free lime remaining turn pink.

A freshly exposed sample is required. For a pipe section, the sample must be extracted (see Cut-Out Sampling and/or Core/Coupon Sampling reviews).

### F56.2 Main Principles

Phenolphthalein is a pH indicator that changes color, from colorless to pink/red in alkaline environments where the pH is greater than approximately 9.6; below this pH the indicator remains colorless. Since free lime has an alkalinity of approximately 12.5, the phenolphthalein indicator test is a good indicator of free lime. The depth of carbonation and/or leaching in cementituous materials can thus be detected.

Cementituous materials become carbonated due to the action of carbon dioxide; carbon dioxide reacts with moisture in the cement/concrete to form carbonic acid. This then reacts with the free lime to form calcium carbonate. The rate of carbonation is dependent on the permeability and moisture content of the concrete. Over time, the depth of carbonation will increase.

Leaching of free lime occurs when water in contact with the concrete/cement surface dissolves free lime, which is then transported away. This occurs in situations where running water is in contact with the asset, such as for asbestos cement pipelines.

The service life of concrete assets with steel reinforcement depends on the ability of the concrete to protect the reinforcement from corrosion. In good quality reinforced concrete, the steel reinforcement is chemically protected from corrosion by the alkaline nature of the concrete. The highly alkaline environment promotes the formation of a passive and protective oxide layer around steel reinforcing bars (Campbell et al, 1991).

The lack of free lime at the surface of the steel reinforcement reduces the alkalinity to the point where the passive protection layer cannot be maintained. The steel reinforcement is therefore free to corrode in the presence of moisture and oxygen. This will eventually lead to spalling of the concrete and failure of the asset.

As above, the tensile strength of a concrete or asbestos cement pipe also falls over time due to the removal of free lime. Free lime can be leached (washed) out of the cement matrix by water, or can be chemically converted by carbonation.

### F56.3 Application

The phenolphthalein indicator test is used to detect the presence of free lime in cementituous assets.

### F56.4 Practical considerations

- Phenolphthalein indicator is widely used in a number of industries as a general indicator of alkalinity. For this reason it is readily available from numerous suppliers.

For the purpose of indicating the presence of free lime phenolphthalein indicator is simple to use and widely used for condition assessment.

- When conducting testing all dust created in exposing the surface to be tested should be removed as this can give false readings. Where holes have been drilled into slabs of material, the edges of the holes should be chipped at to expose a fresher surface prior to testing.
- The boundary between free lime and carbonated material is blurred due to variations in material structure. Repeatability in the tests is good; variation of ± 5mm has been found (Campbell et al, 1991).
- The phenolphthalein test can be conducted on-site or in the lab and requires a freshly exposed surface as carbonation begins immediately on exposure to air.

## F56.5 Advantages

- Phenolphthalein indicator is readily available and easy to use. The test is cheap, fast and simple to conduct. The test can be conducted in the field or in the lab.

## F56.6 Limitations

- Test requires some damage to the asset being tested.
- Phenolphthalein indicator solution is flammable and appropriate precautions need to be taken.
- Phenolphthalein indicator should not be ingested.

**Table F-58. Summary Phenolphthalein Indicator (Carbonation Testing).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Any cementituous asset type, civil also. |
| | Material type | Cementituous materials only. |
| | Service area | Potable and wastewater. |
| | Access requirements | Freshly exposed sample required. For pipes section must either be extracted or a core sample taken. |
| | Limitations relating to asset condition | No restrictions. |
| | Limitations relating to asset size/geometry | No restriction. |
| | Continuous/discrete | Discreet. |
| | Destructive/non destructive | At least part of the asset is damaged/removed to allow testing. |
| | Interruption to supply/function | Non-pressure pipes can remain in use if only a core is taken above flow. Pressure pipes need to be taken off-line for sample removal/testing. |
| Technical suitability | Assessment parameters | Remaining free lime, used to infer carbonation depth. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Widely available. |
| | Previous/existing use of the tool in sector | Widely used. |
| | Accuracy/reliability | Qualitative indicator; the boundary between carbonated and non-carbonated areas is some what blurred, others areas are clearly identifiable. |
| | Ease of validation of results | Direct measurement. |

| | Criteria | Assessment |
|---|---|---|
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy test to conduct by following simple procedure. |
| | Technology required (level of tool sophistication) | No sophisticated tools required to conduct test. Specialized tools may be required to obtain samples depending on location and type. |
| | Documentation | No known standard test methods. Specific chemical information can be obtained from MSDS, CAS# 77-09-8. |
| | Availability of technical support | Knowledge of phenolphthalein is widespread and easily obtainable. |
| Economic factors | Cost per inspection | Low cost. |
| | Resource requirements | Resources are required to obtain sample, e.g., exposing pipeline and removing sample. |

## F56.7 Bibliography


1. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
2. Randall-Smith, M., Russell, A. and Oliphant, R., *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992
3. Campbell, D., Strum, R. and Kosmatka, S., *Detecting Carbonation*, Concrete Technology Today, Volume 12, Number 1, 1991

# F57.0 Pipe Potential Surveys

## F57.1 Overview

Pipe potential surveys are used to gain an understanding of the electrochemical interaction between ferrous pipes and the surrounding soil. The pipe-to-soil potential is measured using a voltmeter and a reference electrode. If electrical connection to the asset can be made above ground, for example connection to a valve, this does not require exhumation of the pipe.

The pipe-to-soil potential measured during testing is useful for identifying areas of for further analysis, including areas where coatings have deteriorated or been damaged. However, some practitioners consider the application is limited for coal tar enamel coatings due to the high number of defects generally found in these coatings.

## F57.2 Main Principles

There are two main types of pipe potential survey. For pipelines with a high quality external protective coating, a Direct Current Voltage Gradient (DCVG) survey can be used to determine the location of gaps in the coating.

The technique involves imposing a direct current on the pipe and measuring the difference in the pipe-to-soil voltage between two reference electrodes ($Cu/CuSO_4$), which are gradually moved along the whole length of the main. At gaps in the coating, the imposed electrical current leaks to earth and there is a significant increase in the voltage gradient compared to sections of the main where the coating is complete.

The second survey technique determines the pipe-to-soil potential along the length of the main using a single reference electrode ($Cu/CuSO_4$) and without an imposed current. This approach is most useful for mains that have either a low quality or no external coating and where electrical continuity is created by the run lead method of jointing.

In order to convert pipe-to-soil potential into corrosion rate, information is required about the soil in which it the potential measured. This requires the soil to be sampled every 50 to 100 meters. Sections of the main in different soils are then exposed and their external condition directly assessed in order to ‘calibrate’ a particular value of pipe-to-soil potential.

A variant of the second form of pipe potential survey should be carried out on a regular basis where a cathodic protection system is installed. If a pipe’s potential is not suppressed sufficiently ($\leq$-850 mV $Cu/CuSO_4$ scale) it will continue to corrode. If its potential is suppressed too much ($\approx \leq$-1200 mV $Cu/CuSO_4$), excessive alkali can be produced at the pipe surface leading to the possibility of delaminating of the protective coating.

## F57.3 Application

Pipe potential surveys measure the voltage between ferrous pipes and the surrounding soil. The technique is most applicable to continuously welded steel pipes, which have good quality external coatings. The voltage can either be the result of an applied current, in the case of DCVG testing, or electrochemical corrosion cells.

Other techniques are also available which rely on similar techniques, including the Pearson Survey, the Current Attenuation Survey and the Close Interval Potential Survey. The Pearson Survey and the Current Attenuation Survey are used to assess the condition of pipe external linings. The Close Interval Potential Survey is used to determine the level of cathodic protection throughout a pipeline.

- BS 7361 refers to some of these techniques.

## F57.4 Practical considerations

- For the DCVG technique to work, the main has to be electrically continuous. This is usually the case with steel pipes joined by welding, where the condition of the external coating is critical for the satisfactory long term performance of the main.
- To measure the pipe-to-soil potential, a fine insulated trailing wire is connected to the pipeline, preferably at an accessible point such as a valve or air valve. The other end is connected to a voltmeter and then the copper/copper sulfate electrode(s). When in contact with the ground, the electrodes complete the electrical circuit and allow the pipe-to-soil potential to be read from the voltmeter.
- Pipe potential readings are taken periodically along the pipeline. At any distance, a constant reading provides some confidence in the results. In contrast, a wildly varying voltage could indicate the presence of stray current or interference from other pipes.
- Water mains coated with coal tar enamel (the default coating in many areas up until the 1980/90's) will invariably find numerous coating defects, and in some cases continuous defects where the coating has split due to soil stresses.

## F57.5 Advantages

- The techniques are non-destructive and can be successful in locating corrosion hotspots.
- Technique may not require a pipe to be exhumed for examination and pipelines can remain in service.
- Locates areas of likely corrosion and indicated if more invasive assessment is required.

## F57.6 Limitations

- Varying moisture contents in soils over the year will cause variation in results.
- Techniques may miss very small isolated areas of corrosion.
- Results are affected by the presence of stray currents.
- The more advanced techniques require highly specialized equipment and trained personnel.

**Table F-59. Pipe Potential Surveys.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Buried pipes. |
| | Material type | Externally coated ferrous pipes. |
| | Service Area | Potable and wastewater. |
| | Access requirements | Electrical contact with asset is required. |
| | Limitations relating to asset condition | DCVG requires pipe to have a good coating (used for locating flaws in coatings). Not such requirement for pipe-to-soil testing. |
| | Limitations relating to asset size/geometry | Limited to continuously welded steel pipe. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Non-destructive test. |
| | Interruption to supply/function | Inspection can be undertaken on-line. |

| | Criteria | Assessment |
|---|---|---|
| Technical suitability | Assessment parameters | Measures electrical potential between a pipe. and surrounding soil to locate areas of corrosion potential. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Tools are fully commercialized. |
| | Previous/existing use of the tool in sector | Pipe potential surveys are widely used in the gas industry and to a lesser extent in the water industry. |
| | Accuracy/reliability | Quantitative; techniques are considered to be reliable. |
| | Ease of validation of results | Results can be validated by exposing of pipe. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Operators require training; specialized training is required where electrical currents/potential is applied to pipes. |
| | Technology required (level of tool sophistication) | Pipe-to-soil technique requires specialized though widely available equipment. Other techniques require specialized equipment and training of personnel. |
| | Documentation | BS 7361. |
| | Availability of technical support | From service providers. |
| Economic factors | Cost per inspection | Depends on technique used. |
| | Resource requirements | Depends on technique used. |

## F57.7 Bibliography


1. Klechka, E. (2004) *Corrosion Protection for Offshore Pipelines*, Coatings for Corrosion Protection, Colorado School of Mines; Accessed November 2006 at: http://www.mines.edu/outreach/cont_ed/coatings1b.htm
2. TechCorr (2005) Pipeline Surveys, TechCorr; Accessed November 2006 at: http://www.techcorr.com/surveys/index.htm

# F58.0 PiReP/PiReM

## F58.1 Overview

The Pipe Rehabilitation Planning System (PiREP) software is a decision support tool for the management of rehabilitation planning in water supply systems. The software currently consists of two modules, supporting both long-term strategic rehabilitation management and mid-term rehabilitation planning.

Strategic planning is undertaken by estimating the annual rehabilitation rates, based on analysis of failure data for groups of pipes and other operational and environmental parameters. Mid-term planning is facilitated using a subjective (weighted) risk ranking approach that provides a priority list of assets.

Pipe Rehabilitation Management (PiReM) is currently under development and is an enhanced version of the PiReP software.

## F58.2 Main Principles

The software was developed as part of a PhD thesis undertaken at the Institute of Urban Water Management and Water Landscape Engineering at Graz University of Technology, and has had only limited use within water authorities.

The existing software includes two modules that analyze long-term and medium-term rehabilitation strategies. These modules are to be revised with further development of the economic and business management aspects. The addition of GIS functionality is planned.

The main part of the strategic long-term rehabilitation planning is the estimation of annual rehabilitation rates for groups of pipes considering pipe attributes, existing environmental influences, aging parameters and failure rates. This requires data from several years of network operation. The boundaries for the annual planned rehabilitation are given by calculating pessimistic and optimistic rehabilitation needs.

The medium -term rehabilitation planning module identifies pipes requiring rehabilitation based on various technical, economical and business management criteria. Criteria such as high failure rate, potential for corrosion, unusual diameter and unusual material are considered. The module uses a subjective risk ranking approach to prioritize assets. The resultant priority list can then be used for the annual planning of future period of five years.

## F58.3 Application

- The software is designed for the long term and medium term rehabilitation planning of water supply networks.

## F58.4 Practical considerations

- The software tool is not fully commercialized; though the PiReP software has been utilized by two Austrian water supply companies.

## F58.5 Advantages

- The software allows detailed scenario analysis to be undertaken, which permits authorities to see the results of modifying rehabilitation rates. This allows the financial needs for long-term rehabilitation to be estimated.
- The mid term rehabilitation module provides a priority list of assets that can be used to guide annual planning for a future period of five years.

## F58.6 Limitations

- Non commercial software that has only had limited use in Europe.
- Requires several years of network failure data. Consequently, the software is not well suited for small authorities or authorities with only limited data.

**Table F-60. Summary PiReP/PiReM.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, water pipeline infrastructure. |
| | Granularity | System and asset level. |
| | Service area | Potable. |
| Technical suitability | Focus of analysis | Decision support system for the rehabilitation planning management of water supply systems. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good asset data is available. |
| | Commercialization | Non commercial software, although commercial release is intended. |
| | Previous/existing use of the tool | Only been used by several European water authorities during its development. |
| | Ease of validation | Validation through statistical analysis. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Potable only; asset to system level. |
| | Integration with other tools/GIS | Requires standard GIS shape files and database files for GIS implementation. |
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management where good asset data is available. |
| | In-house skills required | Asset manager/engineer. |
| | Technology required | PC based tool. Windows based operating system. Needs GIS and spatial data. |
| | Documentation | Only limited documentation available. Has been based on the German standards DVGW W 401. |
| | Data Requirements | Good quality asset data and asset failure history data is required. |
| | Linking to asset data | Uses an authorities GIS data base to transfer information. ESRI shape files and dbf data files are required. No direct link to GIS is provided. |
| | Availability of software and technical support | Only limited support available at this time. |
| | Usability | Software still under development. |

## F58.7 Bibliography

1. Kainz, H., Gangl, G., and Fischer, W. *PiReM – Pipe Rehabilitation Management: Decision Support System for the rehabilitation management of water supply systems*, Graz University of Technology. Website accessed November 2006 at: http://www.sww.tugraz.at/sww/Projekte/pirem/Offizielle_Beschreibung_PiReM_englisch_neu_2005.08.01.pdf

# F59.0 Pit Depth Measurement

## F59.1 Overview of Inspection Tool

Pit depth measurement is a manual technique used to infer corrosion rates of ferrous materials.

Samples are sand blasted and inspected for pitting; the depth of pits are measured using a pointed micrometer or needle-point depth gauge. The corrosion rate is then estimated, with care taken not to underestimate results due to corrosion products remaining in the pits (Dorn et al., 1996). Pit depth measurements can be undertaken as a non-destructive technique in the field, or a pipe section can be removed for testing in a laboratory.

## F59.2 Main Principles

The corrosion of ferrous pipe materials commonly occurs preferentially in localized areas, resulting in the formation of pits. In order to measure the depth of corrosion pits, the pipe surface must be sand/grit blasted to remove corrosion products. In situations where a large number of pits have formed, visual inspection is used to identify the 10 deepest pits for measuring. However, where only a small number of pits are present they should all be measured (Dorn et al., 1996).

Pit depth can be measured using several manual instruments, the most appropriate for a situation depending on the size of the pits found. Larger pits can be measured on site using pointed micrometer or needle-point depth gauge. Smaller pits need to be examined under a microscope to determine pit depth (Dorn et al., 1996).

Pit depth alone does not give an indication of asset condition; knowledge of original wall thickness, general corrosion depth and age are also required to estimate the corrosion rate and thus remaining life of the asset.

## F59.3 Application

Pit depth measurement is relevant only to ferrous materials. Pit depth measurement can be carried out on site and in the laboratory. More advanced pit depth measurements and those for small pits require laboratory facilities.

- No standards or other documentation found on pit depth measurement, however ASME B31G-1991 relates to determining the remaining strength of corroded pipelines.

## F59.4 Practical considerations

- Detailed knowledge of the original wall thickness and general corrosion depth is sometimes difficult to obtain.
- The age of the pipe may not always be relevant in calculating corrosion rate, as in the case of coated pipelines, since corrosion begins only after failure/removal of this coating. For these reasons, corrosion rate estimates should be considered relatively uncertain and this uncertainty should be considered in decision making
- Equipment for manual measurement of pit depth is widely available for a number of commercial suppliers. Field pit depth measurement equipment is easily portable and simple to use. Lab-based equipment requires skilled operators and can require difficult sample preparation. Both field and lab techniques give accurate results, though lab-based techniques are more accurate and able to measure smaller pits.

- Attention is required to ensure that all corrosion products are removed prior to pit depth measurement. Corrosion of cast iron results in graphitization which retains the shape of the pipe disguising locations of corrosion.
- Manual measurement in other pipeline sectors has been generally superseded by other techniques. However, the approach is still used in the water sector.

## F59.5 Advantages

- Simple technique for field measurements giving accurate results.

## F59.6 Limitations

- Without knowledge of original pipe wall thickness, pit depth measurement cannot be used to estimate remaining life of the pipe.
- Pit depth will be underestimated if the depth of general corrosion surrounding the pit measured is unknown and so underestimate the actual corrosion rate.
- Coatings will limit the accuracy of corrosion rate estimations, as pitting will only begin after failure of this coating.
- Manual pit depth measurement is time consuming.

**Table F-61. Summary Pit Depth Measurement.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Buried assets. |
| | Material type | Ferrous materials only. |
| | Service Area | Potable and wastewater. |
| | Access requirements | Pipes must be extracted for lab measurements, field measurements can be preformed in situ. |
| | Limitations relating to asset condition | Any coating and/or corrosion products on the asset need to be removed prior to measurements. |
| | Limitations relating to asset size/geometry | No restriction due to size of asset. |
| | Continuous/discrete | Results are discreet. |
| | Destructive/non destructive | Field measurements are non-destructive. Lab based measurements require sections to be cut from pipe. |
| | Interruption to supply/function | No interruption to supply when done in situ. |
| Technical suitability | Assessment parameters | Pit depth only. |
| | Integration with software tools | Results need to be used in conjunction with other data to obtain useful information. |
| | Commercialization of tool | Equipment is widely available. |
| | Previous/existing use of the tool in sector | Wide use in the sector. |
| | Accuracy/reliability | Measurement accuracy is high. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Some training is required for field level measurements. Lab level measurements require specialists. |
| | Technology required (level of tool sophistication) | Low level technological sophistication required from field level measurements. For lab level measurements specialist equipment is required. |
| | Documentation | No standards or other documentation found on pit depth measurement, however ASME B31G- |

| | Criteria | Assessment |
|---|---|---|
| | | 1991 relates to Determining the Remaining Strength of Corroded Pipelines. |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | Can be expensive due to man hours required |
| | Resource requirements | Resources are required to obtain sample, e.g. exposing pipeline, sandblasting asset surface. Removal of sample may be required. |

## F59.7 Bibliography


1. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
2. Randall-Smith, M., Russell, A. and Oliphant, R. *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992

## F60.0 Process Control Systems (Integrated)

### F60.1 Overview of Tool

An overall Distributed Control System (DCS) network monitors/controls assets and provides preventative maintenance data. PLCs and PCs servers are typically connected on an Ethernet ring with all field equipment by a Field bus network.

### F60.2 Main Principles

When a DCS is implemented, all the plant equipment, starters, variable frequency drives, instruments, PLCs etc. are connected together by a field bus network (e.g., Profibus). This allows on-line diagnostics, field device configuration and predictive maintenance from one central point.

Intelligent field devices provide a lot of diagnostic information. Usually field devices offer two kinds of diagnostic information: "on-line" (cyclically retrieved) diagnostic information and "off-line" (acyclically) retrieved information. On-line information offers current status of the device; e.g., major status and fault bits stored in the device itself. Off-line information includes more detailed information about the device. This detailed information also includes historical information stored in the device itself. Both can be accessed with the equipment in operation.

### F60.3 Application

Motor control centers starters (and connected equipment), variable frequency drives, instruments and any other plant items that can be connected to the Field bus network.

- ISO 13374-1:2003; establishes general guidelines for software specifications related to data processing, communication, and presentation of machine condition monitoring and diagnostic information.

### F60.4 Practical Considerations

- Wide use throughout manufacturing industry. Starting to be used in water industry; the industry is moving towards fully networked control systems.

### F60.5 Advantages

- Automatic records can be kept and trends observed.
- Fieldbus technologies offer some savings in wiring and cross connections costs and reduced commissioning costs. Field devices can be tested, commissioned and configured on-line through the network. Checking device parameters can also be done through the DCS system on-line.

### F60.6 Limitations

- Not readily applied to existing plant as requires substantial infrastructure changes and associated costs. Ideal for green field sites or where major new plant is being installed.

**Table F-62. Summary Process Control Systems (Integrated).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | All 'intelligent' devices. |
| | Material type | N/A |
| | Service area | Potable and wastewater. |
| | Access requirements | Field bus network is required with component parts connected to it. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Continuous. |
| | Destructive/non destructive | Non-destructive gathers data from on board memory device. |
| | Interruption to supply/function | On-line. |
| Technical suitability | Assessment parameters | Current / historical status of component. Status and condition (faults/healthy), number of trips. |
| | Integration with software tools | Required to be part of a filed bus system. |
| | Commercialization of tool | Fully developed and off the shelf. |
| | Previous/existing use of the tool in sector | Becoming widespread. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Depends on application, if for example current drawn by starter, then this can be validated by clamp on ammeters. |
| Utility technical capacity | Asset management sophistication required | Aimed at a higher level of sophistication. |
| | Skills required (level of tool sophistication); usability | Once set up an operator can view condition status data. |
| | Technology required (level of tool sophistication) | Field bus network. |
| | Documentation | Tool is documented. Standard ISO 13374. |
| | Availability of technical support | Yes by supplier of fieldbus technology. |
| Economic factors | Cost per inspection | N/A |
| | Resource requirements | Overall control system can automatically produce reports. |

## F60.7 Bibliography

1. ISO 13374-1:2003 : Condition monitoring and diagnostics of machines - Data processing, communication and presentation - Part 1: General guidelines

# F61.0 Pull-off Adhesion Testing

## F61.1 Overview of Tool

Pull-off adhesion testing measures the adhesive strength of applied coatings to metal, concrete, masonry, plastic and wood. The strength of epoxies, mortars, plasters, bituminous coats, paint finishes and metal coatings can be measured. The surface strength of concrete and other materials can also be tested directly.

The mechanical tensile strength is tested by applying a perpendicular force, either to destruction or until the applied force reaches a prescribed value. For this reason the test may be fully non-destructive in certain situations. However, the review below assumes that testing continues until coating failure.

## F61.2 Main Principles

Pull-off adhesion testing involves measuring the mechanical tensile strength of a coating by applying an increasing stress to the test surface until the weakest path through the material fractures. Test equipment generally consists of a hydraulic hand pump, an actuator, test disks or dollies, an abrasive pad, a cutting tool, adhesive, adhesive mixing sticks and palettes, a drilling template and drill bits for thick coatings.

During testing, the test dolly is attached to the coating surface with an adhesive. Force is then applied perpendicular to the surface to maximize tensile stress as compared to the shear stress (Figure F-11). Failure will occur along the weakest path within the system comprised of the test fixture, adhesive, coating system and substrate. The weakest path could be along an interface between the test fixture and the coating, the coating and the substrate, a cohesive fracture within the coating, a cohesive fracture of the substrate (e.g., concrete) or a combination of these. Test results are generally given as a pressure, psi or MPa, and can be related to the strength of adhesion to the substrate.

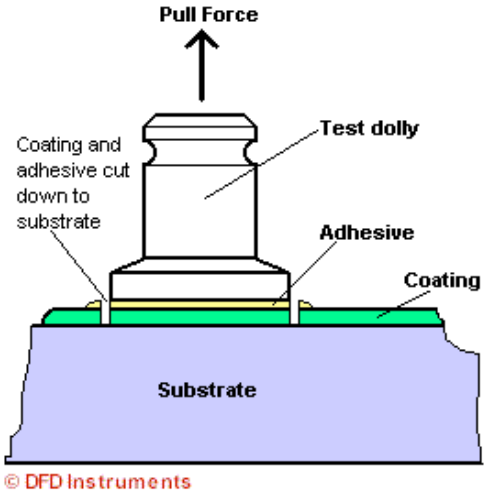


**Figure F-11. Basic Pull-Off Test Setup**
**(Reprinted with permission from: Kolsaker, T., DFD Instruments, 2006).**

## F61.3 Application

Pull-off adhesion testing can be used to test the surface strength of any asset. This primarily applies to assets to which coatings have been applied, but the surface strength of materials such a concrete can also be tested.

- ASTM C4541, ASTM D4541, BS 1881 Part 207 and ISO 4624 (EN 24624) all define the method and procedures for carrying out pull-off adhesion testing of paints, varnishes and other coatings.

## F61.4 Practical Considerations

- Pull-off test equipment is widely available and falls into two general categories, manually and automatically applied force. The choice of equipment usually depends on several factors such as the type of coating, the amount of testing required, test procedure specifications, and personal preferences.
- A range of different sized pull-off adhesion testers are available for measuring coating adhesion on a variety of substrates. For instance a 20mm dolly is ideal for metal, plastic and wood substrates, while a 50mm dolly is recommended for masonry substrates such as concrete. Custom dolly sizes are used to meet specific measuring needs.
- The testing standards emphasize that the speed of tensile force increase must be constant and within specified minimum and maximum values and also consistent from test to test. For these cases, automatic testers are required rather than manual testers.
- Pull-off test equipment is portable so that testing can be conducted in a wide variety of locations.
- The measurement range of equipment varies with the specific surface it was designed for. Many pull-off adhesion-testing pressure systems are calibrated and certified to at least ± 2% accuracy and 0.01 $N/mm^2$ resolution. The certified stress range will generally not cover the full stress range possible by the tester.
- Test equipment with a self-aligning dolly enables measurement on smooth or uneven surfaces without adversely affecting the test results.
- In order to enable the testing of thick coatings, a drilling template is used for isolating the test area from the surrounding coating.
- Powerful pull-off adhesion testers have been designed particularly for tensile adhesion testing of the strongest thermal sprayed coatings (e.g., arc, plasma and HVOF sprayed). These testers have a certified testing range of 19700 psi (136 MPa). This is higher than the tensile strength of the strongest heat-curing adhesive (used for gluing the test elements).

## F61.5 Advantages

- Pull-off testing can be conducted on a wide variety of substrates and coatings.
- Testing is not limited to flat surfaces; curved surfaces such as pipes can be readily tested.
- For concrete coatings, there is no need to embed the sample in the concrete substrate first.
- Self-aligning dolly systems enable force to be consistently distributed over the test area, preventing earlier failure.

## F61.6 Limitations

- Measurements are limited by the strength of adhesion bonds between the loading fixture and the specimen surface or the cohesive strengths of the adhesive, coating layers, and substrate.

- This test can be destructive and spot repairs may be necessary.
- If the dollies are not cleaned sufficiently, 'glue failure' can occur during testing, resulting in an inaccurate. Self-leveling pull testing devices can produce far too low-test results if the pull stress is not 100% evenly distributed throughout the pulled coating. If not, the area where the stress is concentrated will fracture long before maximum stress has been reached elsewhere resulting in low readings.

**Table F-63. Summary Pull-off Adhesion Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Metal, concrete, masonry, plastic and wood assets which are covered in applied coatings, mortars, plasters, bituminous coats and paint finishes. |
| | Material type | Metal, concrete, masonry, plastic and wood. |
| | Service area | Potable and wastewater. |
| | Access requirements | Direct contact with asset coating. If asset is buried then it must be exposed. Surface coatings should be cleaned. |
| | Limitations relating to asset condition | Coating must not be too deteriorated. |
| | Limitations relating to asset size/geometry | No limitations relating to size. Small diameter curved surfaces are more difficult to measure. Specialized models 'micro testers' have been designed for the testing of small test elements and of fragile material. |
| | Continuous/discrete | Discrete reading. |
| | Destructive/non destructive | Overall non-destructive, a small patch of coating is removed from asset. |
| | Interruption to supply/function | The asset can remain in use and does not need to be taken off-line if the coating being tested is external. The testing of internal coatings will require for the asset to be taken off-line in order to allow testing to occur. |
| Technical suitability | Assessment parameters | The adhesive strength of applied coatings and the surface strength of concrete. |
| | Integration with software tools | Stand alone tool and automatic digital adhesion testers are available. For digital adhesion testers the stress increase rate is controlled automatically by a computer and can be set to comply with the relevant adhesion testing standard. |
| | Commercialization of tool | Tool is fully developed, exists in manual and digital forms and is available from a range of commercial vendors. |
| | Previous/existing use of the tool in sector | Widespread use throughout the water and other sectors. |
| | Accuracy/reliability | Some testers are calibrated and certified to ± 1%. Generally testers have ± 2% accuracy and 0.01 $N/mm^2$ resolution. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy to use by following simple procedure. Basic training in achieving correct alignment of the testing machine is recommended. The aim of this is to avoid substantial unwanted stress concentrations in the tested material, resulting in premature fracture of the sample. |

| | Criteria | Assessment |
|---|---|---|
| | Technology required (level of tool sophistication) | Low level of technological sophistication is needed for hand held, manual tools. For digital tools the stress increase rate can be controlled automatically by computer. |
| | Documentation | ASTM D4541, ACI 503-30 USA, ISO 4624 (EN 24624) and BS 1881 Part 207. |
| | Availability of technical support | Technical support widely available from distributors. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | One operator required. Pneumatic or mains powered. Resources required can also depend on asset being inspected. Buried assets need to be exposed. |

## F61.7 Bibliography


1. ASTM D4541 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers
2. ASTM C4541 Pull-Off Strength of Coatings Using Portable Adhesion Testers
3. ISO 4624 (EN 24624) Paints and varnishes -- Pull-off test for adhesion
4. BS 1881 Part 207 Testing Concrete Part 207: Recommendations for the Assessment of Concrete Strength by Near-to- Surface Tests
5. DFD Instruments, http://www.dfdinstruments.co.uk/topics/Study5-ASTM-D4541.htm, accessed 2006

## F62.0 Radiographic Testing

### F62.1 Overview

Radiography is the use of radiation to obtain a picture (radiograph) of an object. The intensity of radiation transmitted through the object is recorded, using a photosensitive film or digital recorder. The process is very similar to x-ray radiography in a hospital; possible imperfections are indicated as density changes on the film in the same manner as a medical X ray shows broken bones.

Radiography is a non-destructive technique that has been used to examine ferrous, cementituous, and plastic pipes (though not GRP). The radiograph shows variations in material and structure, including changes in density (such as associated with corrosion products), inclusion of material ingredients (for plastic pipes), and changes in thickness. It can also be used for inspection of valves.

### F62.2 Main Principles

Traditionally a source of radiation, either gamma or x-rays, was passed through the material and directed onto a photographic film. There is however a trend to replace radiography film by non-film type radiation detectors; digital radiography uses radiation detectors for real time radiographic imaging.

Gamma rays emitted from isotopes (usually Iridium-192, Cobolt-60) are used for ferrous and cementituous materials. X-rays created by cathode-ray tubes are used for plastic materials.

According to the WRc Trunk Main Structural Condition Assessment Manual, there are three variations on the basic technique used in the water sector:

- ***Single Wall Single Image***: Here the radiation source is put inside the object under examination and the photographic film placed on the outside; the radiation passes through a single wall thickness before reaching the film.
- ***Double Wall Single Image***: Here the radiation source is placed outside the object under examination and the photographic plate positioned externally on the opposing side. The radiation passes through two walls before reaching the film. However, because of the intensity of the beam, the features of the wall nearest the source become obliterated and only those of the wall nearest the film are recorded.
- ***Double Loading***: This approach is used to radiograph the features of two adjacent objects between source and film. Two films with different speeds are placed one on top of the other and exposed for the same time. The result is that the slow film records the features of the object closest to the source, with the second object under exposed, and the fast film records the second object from the source with the one nearest over exposed.

Details of the material structure can be seen on the radiograph; darker areas correspond to thinner or less dense material. The features on the film can thus be interpreted in a semi-quantitative manner:

- For ferrous materials, the technique is suitable for detecting pits, due to the difference in density between corrosion products and the parent metal. Since corrosion products are less dense, they appear darker on the radiograph. Calibration is required to estimate the thickness of the corrosion.

- For cementituous materials, radiography can be used to check for voids. The condition of reinforcement in pre-stressed concrete pipe has also been examined using these techniques.
- For plastic materials, the radiograph can detect inclusions or manufacturing voids; X-ray analysis has been used to determine the distribution of lead stabilizers in PVC-U pipes.

Gamma radiography has also been used to check welds in pipelines that carry natural gas or oil. Special film is taped over the weld around the outside of the pipe. A machine carries a shielded radioactive source down the inside of the pipe to the position of the weld. The radioactive source is then remotely exposed and a radiographic image of the weld produced on the film. This film is then developed and examined for signs of flaws in the weld.

## F62.3 Application

In the water sector, the techniques have been used to examine the condition of pipes and valves in situ. In process industries, radiography has been proven to be very useful in detecting different kinds of internal deposits in pipes.

## F62.4 Practical considerations

- Radiography is one of the most commonly used NDE methods in petrochemical processing plants. It is understood this technique is not used within the United States water sector, though it has been used in the United Kingdom water sector.
- Radiography has to be carried out by trained staff aware of all the health and safety issues involved in the use of ionizing radiation. In addition, a certain amount of experience is required to interpret the radiographs produced.
- Exposure times are dependent on section thickness; thicker sections require relatively longer exposure periods. Similarly, water filled pipes also require relatively longer exposure times compared to air filled pipes. For pipe diameters greater than 380 mm (that is, 15”), the main has to be drained down because water is an effective absorbent of γ-rays. Even for smaller diameters, there is a significant reduction in clarity of the radiographs if water is present
- X-ray sets can only be used when electric power is available and when the object to be X-rayed can be taken to the X-ray source and radiographed. Radioisotopes have the advantage that they can be taken to site and no electric power is needed.

## F62.5 Advantages

- The technique can be applied to most materials in situ. It is a non-destructive inspection technique, and details of the material structure can be obtained.

## F62.6 Limitations

- The technique is expensive and there are OH&S issues associated with its use. It examines only a small area of pipe.
- Large diameter mains (> 15”) must be drained down.
- Exposing drinking water to ionizing radiation is not approved or sanctioned by any utility, water industry association, or governmental agency in the United States.
- Experience is required to interpret the radiographs produced.

**Table F-64. Radiographic Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, valves. |
| | Material type | Ferrous, cementituous, plastics (not GRP) |
| | Service area | Potable. |
| | Access requirements | Both sides of the asset must be accessible. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete; small sections only. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Generally would require the asset to be off-line, as water absorbs the radiation. |
| Technical suitability | Assessment parameters | Changes in material structure, including inclusions, corrosion, voids, and thickness changes. |
| | Integration with software tools | Stand alone tool; images need manual interpretation. |
| | Commercialization of tool | Tool and service commercially available. |
| | Previous/existing use of the tool in sector | Limited or no use in the United States water sector; use reported in the United Kingdom water sector. |
| | Accuracy/reliability | Semi-quantitative. |
| | Ease of validation of results | Images can be calibrated; interpretation is a skilled task. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | High level of skill due to health and safety issues; would require specialized contractor to undertake. |
| | Technology required (level of tool sophistication) | Independent of technology. |
| | Documentation | Standards for use are available; documentation also available. |
| | Availability of technical support | N/A; would require specialized contractor to undertake. |
| Economic factors | Cost per inspection | High. |
| | Resource requirements | Requires specialist contractor. |

## F62.7 Bibliography


1. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
2. Randall-Smith, M., Russell, A. and Oliphant, R. *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992
3. IAEA *Development of protocols for corrosion and deposits evaluation in pipes by radiography*, Industrial Applications and Chemistry Section, International Atomic Energy Agency,Vienna, Austria, 2005

## F63.0 Remote Field Eddy Current (RFEC and RFEC/TC Tools)

### F63.1 Overview

The Remote Field Eddy Current (RFEC) inspection technique is a non-destructive method that uses low frequency AC and through-wall transmission to inspect ferrous pipes and tubes from inside the pipe. The through-wall nature of the technique allows external and internal defects to be detected with approximately equal sensitivity.

RFEC probes have been successfully adapted for inspection of cast iron and steel water mains, as well as pre-stressed concrete cylinder pipes (also know as PCCPs).

### F63.2 Main Principles

Eddy current testing is often used to find leaks in large u-tube heat exchanger tubes. In this application, each tube is tested individually. Testing thick walled ferrous pipes from within using conventional eddy current probes is, however, not practical. Very low frequencies are necessary to achieve the through-wall penetration required to detect flaws on the outer surface. This in turn produces low sensitivity. These problems are overcome by the RFEC method. The RFEC inspection technique measures a different phenomenon; the generated AC magnetic field.

The RFEC tool uses a relatively large internal solenoid exciter coil, which is driven with low frequency AC. A detector, or circumferential array of detector coils, is placed near the inside of the pipe wall, but axially displaced from the exciter. The separation between the two coils is between two to five times the internal diameter of the pipe.

Two distinct coupling paths exist between the exciter and the detector coils. The direct path, inside the pipe, is attenuated rapidly by circumferential eddy currents induced in the wall. The indirect coupling path originates in the exciter fields, which diffuse radially outward through the wall. At the outer wall, the field spreads rapidly along the pipe with little further attenuation. These fields re-diffuse back through the pipe wall and are the dominant field inside the pipe at remote field spacing.

A receiver coil that is placed in the remote field zone of the exciter picks up the field. Furthermore, because the pipe wall attenuates the through-wall field, the strength of the field is very sensitive to the wall thickness. Anomalies anywhere in the indirect path cause changes in the magnitude and phase of the received signal, and can therefore be used to detect defects such as cracks, pits or wall thinning produced by corrosion.

RFEC tools are used within the pipe. As such, access requires cut-ins at regular intervals (100 m to 500 m, depending on cable length, pipe alignment, etc). Some tools are adapted for launching through hydrants. RFEC tools are deployed and propelled through the pipe by water pressure or by winching. Computerized software is available for signal interpretation.

When applied to ferrous pipes, the RFEC method is claimed to detect changes in metal mass, graphitization and wall thinning (the direct field eddy current methods are reported to be more sensitive for detection of cracks and voids than RFEC).

A modified version of the tool is used for pre-stressed concrete cylinder pipes (also know as PCCPs) inspection; the RFEC/Transformer Coupling (TC) tool. RFEC/TC testing uses a combination of the remote field effect and the transformer coupling effect. The remote field effect acts as a signal attenuator reducing and slowing the signal sent from a detector coil as is passes out and back in through a metallic pipe wall. The transformer coupling effect acts to amplify and accelerate the transmitted signal in the presence of continuous prestressing

wires. The electromagnetic field energy produced in the RFEC/TC technique interacts with broken pre-stressing wires. Wire breaks interrupt the flow of energy, changing the measured field and allowing for detection of broken wires.

## F63.3 Application

The RFEC method was developed for the inspection of carbon steel components such as process heat exchangers, tanks and boiler tubes.

It allows for the inspection of pipes and tubes from the inside to check for problems around the entire circumference and over the entire length.

RFEC probes have been successfully adapted for inspection of cast iron and steel water mains. A modified version of the tool is used for pre-stressed concrete cylinder pipes (also know as PCCPs) inspection.

## F63.4 Practical considerations

- Tools are commercially available though use requires specialized contractors. Commercial use of the tools is reported in literature and trade journals.
- The sensitivity and resolution of the technique depends on the configuration of the exciter and detector coils. Detector coils with small footprints improve the resolution, but reduce the scanning rate.
- Inspection speeds with RFEC is significantly lower than conventional eddy current (Birring, 1999).

## F63.5 Advantages

- RFEC tools are available to suit a range of pipe sizes 150 mm upwards. The smaller sizes may be launched through modified fire hydrants. The probes can be used in wet or dry conditions.
- Probes with circumferential array of detectors are capable of examining 100% of the pipe. Some tools operate through internal cement linings (up to 25 mm), though with a reduction in sensitivity and resolution.
- The RFEC/TC tool is able detect and resolve multiple regions of broken wires at different axial locations along the pipe.

## F63.6 Limitations

- Pipe requires internal cleaning prior to inspection. If water is used to propel the tool, it is necessary to discharge the water to the environment.
- There is variability in the success of flaw detection and location by probes supplied by different companies.
- Although capable of giving a good estimate of where the wire break occurs along the length of the pipe, the technique can give no information at this time as to the circumferential position of the broken wires.

**Table F-65. Summary Remote Field Eddy Current.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, water and Wastewater pipeline infrastructure, tubes. |
| | Material type | Iron and steel pipes, PCCPs. |
| | Service Area | Potable and wastewater. |
| | Access requirements | Tool only for use within pipe (internal use). Tool access requires cut-ins at regular intervals (100 m to 500 m, depending on cable length, pipe alignment). Some adapted for launching through hydrants. |
| | Limitations relating to asset condition | No limitations relating to asset condition provided direct contact with the pipe wall is available. |
| | Limitations relating to asset size/geometry | Asset must be of sufficient size to accommodate wheeled carriage. Devices to suit 150 mm internal diameter have been produced. These can negotiate bends up to 15º radius. Tools are tailored to specific internal pipe diameters, ±5%. |
| | Continuous/discrete | Continuous readings stored in computer memory in real time and space. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Tool application requires pipe to be off-line. |
| Technical suitability | Assessment parameters | Internal and external defects such as cracks, pits or wall thinning. |
| | Integration with software tools | Computerized software is available for signal interpretation. |
| | Commercialization of tool | Commercialized, availability through specialized companies. |
| | Previous/existing use of the tool in sector | Commercial use of the tools reported in literature and trade journals. AwwaRF reports available on tool sensitivity. |
| | Accuracy/reliability | Quantitative assessment; but varied sensitivity to defects. |
| | Ease of validation of results | Calibration of tool against reference samples required. Validation possible only by comparison with manual/direct measurements. |
| Utility technical capacity | Asset management sophistication | Generic approach. |
| | Skills required (level of tool sophistication); usability | Professional skills required to interpret output data. Tool operation typically by a third party. |
| | Technology required (level of tool sophistication) | Specialized equipment and dedicated computer software. |
| | Documentation | Tool principles and description of reports generated by tool will be available. |
| | Availability of technical support | Tool operation typically by a third party. |
| Economic factors | Cost per inspection | Greater than US$5,000 per site, plus civil costs. |
| | Resource requirements | Typically two-person crew. |

## F63.7 Bibliography


1. Birring, A.S. *Selection of NDT techniques for inspection of heat exchanger tubing*. Proced. Petroleum Industry Inspection Conference, Texas, USA. June 1999
2. Burn, L.S., Eiswirth, M., DeSilva D. and Davis P., *Condition Monitoring and its Role in Asset Planning*, Pipes Wagga Wagga 2001, Charles Sturt University, Wagga Wagga, N.S.W., 2001
3. Dingus, M., Haven, J. and Austin, R. *Nondestructive None Invasive Assessment of Underground Pipes*, AwwaRF, USA, 2002
4. Makar, J. M. ; Chagnon, N. *Inspecting systems for leaks, pits, and corrosion*, National Research Council of Canada, Institute for Research in Construction, NRCC-42802 (downloaded from www.nrc.ca/irc/ircpubs), 1999
5. Rajani, B.; Kleiner, Y. *Non-destructive inspection techniques to determine structural distress indicators in water mains*, National Research Council of Canada, Institute for Research in Construction, NRCC-47068 (downloaded from www.nrc.ca/irc/ircpubs), 2004
6. Lillie, K., Reed, C. and Rodgers, M. A. R., 2004, Workshop on Condition Assessment Inspection Devices for Water Transmission Mains, AwwaRF, USA, 2004

# F64.0 Schmidt Hammer

## F64.1 Overview

The Schmidt hammer is a simple hand held device that allows non-destructive assessment of materials such as brick and concrete. The tool gives an inferred measure of compressive strength by an assessment of surface hardness.

The hammer consists of a spring loaded mass that is fired at the sample and rebounds, thereby measuring the 'rebound number' for the material. A calibration chart is then used to give an indication of compressive strength. Digital versions of the tool give direct readouts of compressive strength.

## F64.2 Main Principles

The Schmidt hammer or rebound hammer indirectly measures compressive strength by measuring surface hardness of materials such as concrete and brick. The original design of the Schmidt hammer was cylindrical, approximately 55 mm in diameter and 275 mm in length (Dorn et al., 1996). Several new designs are now available for use on samples of different geometries, strengths and impact resistances.

In use, the Schmidt hammer is ideally aligned perpendicular to the surface being tested. A spring loaded mass is then fired at the sample. The distance the mass rebounds from the surface of the sample is related empirically to the compressive strength of the sample (Proceq, 2005).

## F64.3 Application

The Schmidt hammer is used to test the strength and quality of concrete and brick assets, both civil and pipeline, and is used in a number of international standards:

- ASTM C 805-97, Svensk Standard SS 13 72 37, Svensk Standard SS 13 72 50, Svensk Standard SS 13 72 52, BS 1881: Part 202.

## F64.4 Practical considerations

- The Schmidt hammer is readily portable and simple and is widely used for testing concrete assets. The Schmidt hammer is available from many commercial suppliers. Results obtained from the manual version of the tool are converted to compressive strength using calibration curves; some digital versions can give compressive strength readouts directly.
- The accuracy of the technique is relatively low for prediction of compressive strength; between ± 15-20% in well controlled conditions (Feldman, 1977). Due to the heterogeneity of cementituous materials, multiple readings (~10) should be taken, although not in exactly the same location.
- The result of this technique should only be used as an indication of material strength. However, it is useful for comparing the relative strengths of different materials or different areas of an asset (Dorn et al., 1996).
- In order to conduct a test using the Schmidt hammer, access to the surface of the asset is required. This means that buried assets must be exposed and surface coatings must be removed. The asset surface may also require abrading to provide a smooth surface. The tool is hand held and so sufficient room is required for personnel.

- Depending on the angle of the Schmidt hammer to the vertical during testing, corrections may need to be made for this angle.

## F64.5 Advantages

- The Schmidt hammer is a quick means of assessing compressive strength of cementituous or rock like materials, and can provide valuable comparative data between different parts of a sample, or between different samples (Dorn et al., 1996).

## F64.6 Limitations

- The accuracy of the technique is relatively low for prediction of compressive strength, between ± 15-20% in well controlled conditions (Feldman, 1977).
- The results are also very dependant on surface conditions (Dorn et al., 1996) and results can be affected by the smoothness of surface, geometry of sample, moisture content, type of cement and aggregate and the extent of surface carbonation (Feldman, 1977).
- The results obtained are for localized areas of the asset due to the heterogeneous nature of cementituous materials (Randall-Smith et al, 1992).

**Table F-66. Summary Schmidt Hammer**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Manholes, pipes, CSOs, civil. |
| | Material type | Concrete, brick. |
| | Service Area | Potable and wastewater. |
| | Access requirements | Direct contact with asset required. If the asset is buried, then it must be exposed. Surface coatings must also be removed. The asset surface may also require abrading to provide a smooth surface. |
| | Limitations relating to asset condition | No limitations relating to asset condition. |
| | Limitations relating to asset size/geometry | No limitations relating to size/geometry for external use on pipes. For internal usage the asset must be of sufficient size for man entry. |
| | Continuous/discrete | Discrete reading. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | For man entry, standard safety procedures should be followed, otherwise the asset can remain in use. |
| Technical suitability | Assessment parameters | Equipment gives a reading relating to compressive strength of asset. |
| | Integration with software tools | No integration with software tools. |
| | Commercialization of tool | Equipment is widely available from commercial vendors. |
| | Previous/existing use of the tool in sector | Widely used to assess the quality of concrete assets. |
| | Accuracy/reliability | Quantitative; readings are ± 15-20% accurate. |
| | Ease of validation of results | Results are only indicative of compressive strength on which can be used. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Easy to use by following simple procedure. |
| | Technology required (level of tool sophistication) | Tool comes in both manual and digital versions, manual versions provide rebound numbers only and compressive strength needs to be obtained |

| | Criteria | Assessment |
|---|---|---|
| | | by reading calibration curves. Digital versions calculate compressive strength. |
| | Documentation | ASTM C 805-97, Svensk Standard SS 13 72 37, Svensk Standard SS 13 72 50, Svensk Standard SS 13 72 52, BS 1881: Part 202. |
| | Availability of technical support | Technical support available from retailers and from Internet. |
| Economic factors | Cost per inspection | Low cost per inspection. |
| | Resource requirements | Resources required depend on assets being inspected. |

## F64.7 Bibliography


1. ASTM C805-02 Standard Test Method for Rebound Number of Hardened Concrete
2. BS EN 12504-2:2001 Testing concrete in structures. Non-destructive testing. Determination of rebound number
3. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
4. Feldman, R.F., CBD-187 *Non-destructive testing of concrete*, Canadian Building Digest, http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd187_e.html , accessed 2005
5. Mastrad: Quality and test systems, http://www.mastrad.com/schmidt.htm , accessed 2005.
6. Proceq, http://www.proceq-usa.com/products/originalschmidt.php , accessed 2005.
7. Randall-Smith, M., Russell, A. and Oliphant, R. *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992
8. SIS; Svensk Standard SS 13 72 37. "Betongprovning-Hårdnad betong-Studsvärde," (Concrete testing - Hardened concrete - Rebound number, in Swedish)
9. SIS; Svensk Standard SS 13 72 50. "Betongprovning-Hårdnad betong- Tryckhållfasthet skattad med ledning av studsvärden," (Concrete testing - Hardened concrete - Compressive strength from rebound number, in Swedish)
10. SIS; Svensk Standard SS 13 72 52. "Betongprovning-Hårdnad betong- Tryckhållfasthet, skattad med ledning av studsvärden och ljudhastighetsvärden," (Concrete testing - Hardened concrete - Compressive strength, rated from rebound and sound velocity values, in Swedish)

## F65.0 SCRAPS (Sewer Cataloging, Retrieval and Prioritization System)

### F65.1 Overview

The Sewer Cataloguing, Retrieval and Prioritization System (SCRAPS) is an expert system that targets the inspection of critical areas of the sewer network.

The knowledge base of this expert system was assembled with input from a national group of experts, drawn from both the public and private sectors. Input from the experts was used to develop the system's logic, which assesses the overall need to inspect a sewer based on the pipe's consequence and likelihood of failure. The inference engine is based on Bayesian belief network theory, which allows the uncertainty in the experts' beliefs to be propagated through the system. The tool was developed with a rapid prototype application process. The validation of the tool showed it is effective at mimicking the knowledge of experts.

### F65.2 Main Principles

SCRAPS assumes sewer collection systems fail when they are unable to convey wastewater from its origin to its prescribed destination without endangering or inconveniencing the public. System failures include releases, overflows, and surface collapse. SCRAPS predicts the criticality of sewer pipelines in terms of how likely the sewer is to fail (likelihood) and the extent of societal impacts if failure should occur (consequence).

SCRAPS is intended to target CCTV inspections on critical areas of the sewer system, thereby reducing the potential cost for emergency repair and delaying unnecessary inspections. The logic in SCRAPS is based on work from the Water Research Centre (WRc, UK), and on a group of eight mechanisms that define the consequence and likelihood of asset failure. These mechanisms constitute the tool's decision making logic. Two of the eight mechanisms, 'Socio-Economic Impacts' and 'Reconstruction Impacts,' define the consequence of failure. The remaining six mechanisms define the likelihood of failure, and include 'Operational Defects', 'Structural Defects', 'Interior Corrosion', 'Exterior Corrosion', 'Infiltration' and 'Erosion'.

SCRAPS has two primary components: 1) an inference engine and 2) a knowledge base. The inference engine defines the mathematical algorithm by which a decision is reached. The knowledge base is the body of information that represents the expert knowledge. The other components of SCRAPS, a graphical user interface and a database, are developed with Microsoft Visual Basic and Microsoft Access respectively.

The knowledge base of the expert system was developed through a process of ''knowledge acquisition.'' Knowledge was acquired and incorporated into SCRAPS by interviewing sewer infrastructure experts, operators, and managers. The knowledge acquisition process was facilitated by a rapid prototyping process that allowed on-going testing of the accuracy of the knowledge base.

### F65.3 Application

The software is designed to facilitate the management of sewerage networks by prioritizing CCTV inspections.

### F65.4 Practical considerations

- The SCRAPS system is available from WERF.
- SCRAPS is principally aimed at small utilities that may not have sufficient system data to search effectively for potential failures.

- The tool is also usable by utilities that have collected considerable data and performed condition assessments. In this case, the tool allows prioritization of repair of the sewers with the highest risk of failure according to the consequences of failure.
- The tool may provide insight in to the factors that have had greatest influence on the current condition.

## F65.5 Advantages

- SCRAPS can assist small to medium sized utilities develop a strategy to gather information about their systems by prioritizing their inspection process.
- The tool targets critical areas of the sewer system first, thereby reducing the potential cost for emergency repair and delaying unnecessary inspections.
- The tool's logic is based on the industry paradigm of consequence of failure and likelihood of failure and extensive input from numerous regional-based experts.
- The tool has the advantage of containing the heuristics and understanding of failure and impact relationships of many experts.

## F65.6 Limitations

- Large authorities may require more sophisticated approaches.

**Table F-67. Summary SCRAPS (Sewer Cataloging, Retrieval and Prioritization System).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Sewer networks. |
| | Granularity | System level. |
| | Service Area | Wastewater. |
| Technical suitability | Focus of analysis | Expert system that prioritizes sewer inspections. |
| | Scalability of tool/approach | Aimed at small utilities that may not have sufficient system data to search effectively for potential failures. |
| | Commercialization | Commercial system available from WERF. |
| | Previous/existing use of the tool | Has been used in the United States. |
| | Ease of validation | Validation is possible through comparison with independent assessments. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Wastewater; system level only. |
| | Integration with other tools/GIS | None. |
| Utility technical capacity | Asset management sophistication | Aimed at level of asset management where standard asset data is available. |
| | In-house skills required | Asset manager. |
| | Technology required | PC based tool. Windows based operating system. |
| | Documentation | Detailed report available from WERF. |
| | Data Requirements | Targets critical assets and requires information on them. |
| | Linking to asset data | Through database. |
| | Availability of software and technical support | Limited support available. |
| | Usability | Windows based software. |

## F65.7 Bibliography

1. Hahn, M.A., Palmer R.N., Merrill, M.,S. and Lukas, A.B. *Sewer inspection prioritization with a regional expert system*. Proc. of the ASCE's 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management, Minneapolis, MN, August, 2000

## F66.0 Slow Crack Growth Resistance of PE Pipes

### F66.1 Overview

The Notched Tensile Test is a destructive test that can be used to quantify the resistance to slow crack growth of a PE pipe material.

The test involves deliberately introducing a razor notch onto a test coupon, which is then subjected to a pre-defined tensile stress. The time to failure is recorded, which correlates with the resistance to slow crack growth exhibited by a particular pipe material

Traditionally used to assess performance of new PE materials, this test has also been used to measure slow crack growth resistance of pipes currently in-service.

### F66.2 Main Principles

The test is conducted on a small coupon (50 mm in length and 25 mm in width) extracted from the pipe wall. The coupon can be extracted so that its longitudinal axis is aligned with either the pipe longitudinal or circumferential directions. The thickness of the coupon corresponds to the pipe wall thickness.

A razor notch is deliberately introduced into the coupon specimen using a razor blade. This razor notch is aligned perpendicular to the longitudinal axis of the specimen. The specimen is then loaded in tension along its longitudinal axis to a pre-defined nominal tensile stress and the time to failure is recorded.

The time to failure correlates with the resistance to slow crack growth exhibited by a particular pipe material. Longer test times correspond to relatively high slow crack growth resistances.

### F66.3 Application

This test is applicable to PE pipe materials only.

- This test method applies to PE pipes and is described by the American Standard ASTM F 1473. The American standard ASTM D 3350 specifies a test temperature of 80°C and a stress of 2.4 MPa. ISO 16241: 2005 also references this test method.

### F66.4 Practical considerations

- This test method is primarily used by PE material and pipe producers to rank the slow crack growth performance of new PE materials. However, some limited studies have also conducted tests on coupon samples from pipes in service and shown reasonable correlation with field performance.
- Specimen preparation (especially notching) requires skill, but clear guidelines are provided in the American standard F 1473. Due to the requirement for elevated temperature, the test method should be conducted in the laboratory.
- Different PE material type classifications are listed in the American standard ASTM D 3350. For a particular PE material type, ASTM D 3350 specifies minimum failure times in the Notched tensile test. Therefore, results from notched tensile tests can be used to determine the material classification of the pipe under inspection. Furthermore, results from notched tensile tests on a wide range of PE materials have also been published in the literature. This provides a basis for comparison in terms of slow crack growth resistance.

- Results from the notched tensile test correlate well with the potential for slow crack growth failure under normal operating loads. In general, longer failure times correspond to lower average slow crack growth failure rates in the field. However, the test does not relate to PE pipe failures that occur under the influence of external factors such as poor pipe installation practice and third party damage during adjacent excavation.

## F66.5 Advantages

- The test method should be relatively low cost.
- A single coupon test will indicate the resistance to slow crack growth of the pipe under inspection.
- With appropriate expertise, comparisons can then be made with previous literature studies in which notched tensile test results were compared with slow crack growth field failures in PE pipes.

## F66.6 Limitations

- The test method is destructive and coupon samples require careful razor notching.
- Test results require comparison with previous studies in the literature to be meaningful.
- Tests conducted on new PE materials can result in impractically long test times.

**Table F-68. Summary Slow Crack Growth Resistance of PE Pipes.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes. |
| | Material type | Polyethylene. |
| | Service area | Potable or wastewater. |
| | Access requirements | Pipe must be exposed and coupon must be extracted from the pipe wall. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Destructive, but the location of coupon removal on the pipe can be repaired using an electrofusion coupling. |
| | Interruption to supply/function | Tests must be conducted off-line in laboratory. |
| Technical suitability | Assessment parameters | The resistance of the pipe material to slow crack growth is measured. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Test method fully developed and included in American standards. |
| | Previous/existing use of the tool in sector | Primarily used as a material research tool but has been applied using coupons extracted from PE gas pipelines in service. |
| | Accuracy/reliability | High degree of accuracy can be achieved in test with commercially available mechanical test and data collection equipment. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | A medium level of operator skill is required for sample notching prior to test. |
| | Technology required (level of tool sophistication) | Mechanical test and data collection equipment are available in many research company test labs. |

| | Criteria | Assessment |
|---|---|---|
| | Documentation | Test method is fully documented in ASTM F 1473. Threshold values for test times distinguishing different PE materials classes are covered in ASTM D 3350. Journal papers quoting typical results for different PE pipe materials in use are available in the literature. |
| | Availability of technical support | University or research organizations can offer support in the use of and interpretation of test results. |
| Economic factors | Cost per inspection | Specialist test, so relatively expensive |
| | Resource requirements | Laboratory based test. |

## F66.7 Bibliography


1. ISO 16241: 2005, Notch tensile test to measure the resistance to slow crack growth of polyethylene materials for pipe and fitting products

2. ASTM F1473, Standard test method for the notch tensile test to measure the resistance to slow crack growth of polyethylene pipes and resins

3. ASTM D 3350, Standard specification for polyethylene plastic pipe and fitting materials

## F67.0 Smart Digital Sewer Pipe Diagnostic System (VTT)

### F67.1 Overview

The Smart Digital Diagnostics System for Sewer Pipes is currently being developed. It is intended to be a new diagnostics system able to interpret digital image data according to future CEN standard (Visual Inspection Coding System).

When completed, the system will measure and analyze the condition of a sewer pipe and will support network wide regular condition monitoring and proactive maintenance.

### F67.2 Main Principles

The approach is intended to be a replacement for CCTV inspection of sewer pipes. The technology used differs from CCTV in that it produces very accurate digital side scans of the pipe wall instead of producing only forward looking continuous images of the pipe. It also produces very accurate on-line location data with the help of two different measurement systems.

In use, the system scans the pipe wall, taking one 1mm ring scans, and produces open folded side scans of the pipe. The image produced is continuous. Besides the side scanning, the tool captures front view images at discrete intervals.

The scanner's inclinometer registers vertical movement and a gyroscope registers horizontal movement. The distance from the starting point is measured from the power cable. If the x, y and z co-ordinates of the starting point and the ending point are given, the system can determine the co-ordinates of the centerline of the pipe.

### F67.3 Application

When developed, the system will provide automated analysis of defects in sewer pipelines.

- It is intended to interpret digital image data according to a future CEN standard (Visual Inspection Coding System).

### F67.4 Practical considerations

- The system is still in the development stages with the focus of the research and development being direct defect analysis.
- When the software is completed, all the measurements and analyzing work will be made immediately on-site after the data is collected.
- Helsinki Water has utilized the system and field demonstrations have been carried out in Germany (Hamburg), Denmark (Copenhagen), Sweden (Malmo), Stockholm, (Gothenburg), Norway (Oslo), Russia (St Petersburg), Latvia (Riga) and Estonia (Tartu).

### F67.5 Advantages

- Enables advanced and automatic analysis of sewer pipelines for defects rather than the manual analysis required with traditional CCTV data. This has the potential in the long term to reduce the costs associated with sewer inspection.

## F67.6 Limitations

- The technique is in its development stages and has only been trialed in a number of European cities.
- The system requires a highly specialized scanner unit.

**Table F-69. Summary Smart Digital Sewer Pipe Diagnostic System (VTT).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Sewer pipelines. |
| | Material type | Any material. |
| | Service area | Wastewater. |
| | Access requirements | Scanner unit is inserted through manhole access point. |
| | Limitations relating to asset condition | Assets in very poor condition may cause the scanner to get stuck. |
| | Limitations relating to asset size/geometry | Scanner unit needs to be inserted into pipeline, so very small diameter pipes are not suitable, although the vast majority of sewer pipes will be covered. |
| | Continuous/discrete | Scanner records continuous data along pie length. |
| | Destructive/non destructive | Non-destructive inspection technique. |
| | Interruption to supply/function | No interruption to sewer is needed. |
| Technical suitability | Assessment parameters | Records high quality digital images with 1mm accuracy that covers the entire circumference of the pipe wall. |
| | Integration with software tools | Requires specialized software to interpret results. |
| | Commercialization of tool | Non commercial product that is still under development. |
| | Previous/existing use of the tool in sector | Has been trialed in several European cities only. |
| | Accuracy/reliability | Quantitative and qualitative. |
| | Ease of validation of results | Validation is possible through visual inspection. |
| Utility technical capacity | Asset management sophistication required | A high level of sophistication is required using specialized equipment and software. |
| | Skills required (level of tool sophistication); usability | Skilled operator required. |
| | Technology required (level of tool sophistication) | Specialized scanner unit is required and dedicated software to interpret results. |
| | Documentation | Technique still in development. |
| | Availability of technical support | Technique still in development. |
| Economic factors | Cost per inspection | Initial purchase costs are high. |
| | Resource requirements | Skilled operator and equipment is required. |

## F67.7 Bibliography

1. Welsh School of Architecture (Data Unknown) Case Study: Digital diagnostics system for sewer pipes. Accessed November 2006 at: http://www.cardiff.ac.uk/archi/programmes/cost8/case/watersewerage/finland-sewer.pdf

# F68.0 Smoke Testing

## F68.1 Overview

Smoke testing is used to identify faulty or illegal connections to gravity sewer and storm water systems.

Fans are used to force artificial smoke into the sewer at one or more manholes. The smoke will then either escape the system at house vent pipes, defective or illegal connections and other problem areas, allowing them to be identified.

## F68.2 Main Principles

Smoke from either smoke bombs or a liquid smoke system is forced into the system at manholes using specially designed fans. The smoke escapes from the system at house vent pipes, illegal connections such as down pipes and faulty connections, allowing them to be identified.

When testing sewer systems smoke should escape from house vent pipes, if smoke escapes from drain pipes this indicates an illegal connection to the sewer system. The reverse is true for storm water systems.

## F68.3 Application

Smoke testing is used to locate illegal or faulty connections to gravity sewer and storm water systems, but can also indicate defective connections buried manholes.

## F68.4 Practical considerations

- By partially blocking pipes leading away from the test area, smoke is not lost to areas not being inspected.
- Residents and emergency service should be fully informed prior to testing to prevent unnecessary distress.

## F68.5 Advantages

- Smoke test systems are inexpensive and provide a fast method for locating illegal and faulty connections.

## F68.6 Limitations

- May cause alarm to residents.

**Table F-70. Summary Smoke Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Gravity sewer and storm water. |
| | Material type | Any. |
| | Service area | Wastewater. |
| | Access requirements | Manhole or similar access to sewer pipes required. |
| | Limitations relating to asset condition | Not restrictions due to asset condition. |
| | Limitations relating to asset size/geometry | No restriction due to size of asset. |
| | Continuous/discrete | N/A |
| | Destructive/non destructive | Testing is Non-destructive. |
| | Interruption to supply/function | Inspection can be undertaken while asset is on-line. |
| Technical suitability | Assessment parameters | Test indicates connections to sewer pipeline. |
| | Integration with software tools | Stand alone tool for detecting locations of inflow. |
| | Commercialization of tool | Equipment is available from a number of commercial suppliers. |
| | Previous/existing use of the tool in sector | Used in the United States. |
| | Accuracy/reliability | Qualitative indication. |
| | Ease of validation of results | Results can be validated by visual or other inspection methods. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Low level of operator skill required. |
| | Technology required (level of tool sophistication) | Specialized equipment required to introduced smoke to assets. |
| | Documentation | No standards were found on this technique. |
| | Availability of technical support | Information on testing can be obtained from equipment suppliers. |
| Economic factors | Cost per inspection | Low cost. |
| | Resource requirements | Test requires a number of personnel for each test to locate smoke escape points. |

## F68.7 Bibliography


1. Hurley, L. *Smoke Testing Our Sewer Systems*, Pipes Wagga Wagga 2005, Charles Sturt University, Wagga Wagga, N.S.W., October 17-20, 2005
2. Ratliff, A. *An overview of current and developing technologies for pipe condition assessment*, Pipelines 2003, ASCE 2004.

## F69.0 Soil Characterization

### F69.1 Overview

Soil characterization involves analyzing soil parameters relevant to the deterioration of buried assets. Such parameters include pH, sulfide concentrations, moisture content, electrical conductivity (salinity), shrink-swell capacity and redox potential. Soil characteristics interact with buried assets of all material types.

Characterization of soil parameters relevant to buried assets allows suitable material types to be chosen and effective preventative measures to be taken to minimize degradation of the asset. Soil characterization can also be used with pipe specific information to predict the working life of the pipe.

### F69.2 Main Principles

When collecting samples for lab characterization or in-situ testing the position of the sample should be relevant to the buried asset. For example, samples should be taken at the depth of the pipe asset instead of at the surface. Soil parameters of interest include:

- ***Soil resistivity***; Soil resistivity is relevant to the corrosion of ferrous materials. Soils with low resistivity are more likely to have high corrosion rates, while high resistivities are likely to indicate low corrosion rates (see section on Soil Resistivity).
- ***pH***; Low pH values are associated with corrosion of ferrous assets and deterioration of cementituous assets. However, while a useful indicator of potential corrosivity, the correlation between pH and corrosion rate is not consistent and can be affected by a number of factors. Deterioration of cementituous materials will be affected by the type of acid present, as some react more readily with the cement than others.
- ***Redox potential***; the redox potential of soil is a measure of soil aeration and gives an indication of the suitability of conditions for sulfate reducing bacteria. The presence of sulfate reducing bacteria can result in the production of corrosive products such as hydrogen sulfide (as a by-product of metabolism), and can create cathodic areas on assets due to the consumption of hydrogen. Redox potentials of below 100 mV are most favorable for sulfate reducing bacteria.
- ***Sulfates*** also react with cementituous materials forming gypsum and ettringite, which have significantly higher volumes than the materials they replace causing swelling and cracking of the pipe wall. Sulfate attack will only occur where the sulfate salt are in solution.
- ***Chloride content***; Chloride ions permeate into cementituous and attack steel reinforcement. Corrosion of the reinforcement results in a volume increase applying stress to the asset resulting in spalling.
- ***Moisture content***; Soil moisture acts as the electrolyte in electro-chemical corrosion of ferrous assets. Static water also acts to produce anaerobic conditions suitable for sulfate reducing bacteria. Static water can also allow sulfates and chlorides to enter solution in close contact with the asset and permeate into cementituous assets (see above). Flowing water can act to leach free lime from cementituous assets (Randall-Smith, 1992). Soil moisture content will also define the degree of saturation of the soil. This will give an indication of the state of soil drying, which is important for moisture migration and soil moisture reactivity (see shrink/swell capacity).

- ***Shrink/swell capacity*** (soil moisture reactivity); Clay soils change volume depending on their water content. Clay particles absorb moisture into their crystal lattice causing them to swell. As the moisture content of the soils reduces due to uptake by plant root systems, percolation through soil matrix and evaporation, the soil will shrink. Assets within soils with high shrink/swell capacities are known to have an increased failure rate, due to the stresses imparted by the soil during the shrink/swell cycle. The basic properties that characterize shrink/swell capacity are plasticity index, fraction of fine particles and the mineralogy of the particles. The mineralogy of the particles may be related to the geologic origin of the soil deposit. Alternatively, direct mineralogical measurements may be carried out to characterize the soil fractions.
- ***Buffering capacity***; Clay soils and soils high in organic matter have high buffering capacity while sandy soils and soils low in organic matter have low buffering capacity (Agri-facts, 2005). A soil's buffering capacity is the degree to which it is able to resist changes in pH; in particular acidification. The affects of pH are covered above.
- ***Linear polarization resistance***; LPR can been used to predict the corrosion rate of buried ferrous assets; high LPR indicates low corrosion rates. The empirical relationship between LPR and corrosion rate has been investigated on a number of occasions, and some doubt has been expressed as to the reliability of the technique (Heathcote and Nicholas, 1998). (see review on Linear Polarization Resistance)
- ***Contaminants***; soil contaminants such as organic compounds can have negative affects on polymeric materials. Organic compounds such as petrol can migrate through the polymeric pipes both impacting water quality and remaining in the polymer matrix causing it to swell and lose strength. Highly levels of acidic continents can also cause environment stress cracking of polymers dramatically reducing lifetime.
- ***Soil compaction***: The susceptibility of the trench filling and the surrounding sediments for compaction.

These parameters often cannot be used in isolation because of the range of factors involved in chemical and electrochemical processes that cause corrosion, deterioration and stress failure (Dorn, 1996). As such, results are often incorporated into scoring systems used to classify a soil's potential for corrosion or other mechanisms of deterioration.

## F69.3 Application

Soil characterization tests conducted on samples taken at relevant locations can be used to give an insight into the environment of buried assets without disturbing the asset.

Characterization conducted prior to installation of buried assets can be used to determine appropriate material type to be used and also establish if any protection measures need to be included, such as cathodic protection.

## F69.4 Practical considerations

- Integration of soil characterization into a GIS system can give a good picture of soil conditions. Soil information, asset characteristics and depth, and groundwater levels can be overlayed within a GIS to identify likely interactions between soil, groundwater and buried assets. This is especially true in cities where the pipe system is in contact with the ground water table, which is a common occurrence in Europe.
- Soil tests are often conducted at failure locations, however, it should be noted that this may give a skewed picture of soil conditions.

## F69.5 Advantages

- Samples can be obtained without exposing buried assets.
- Characterization can be focused on parameters of interest such as those linked to corrosion.
- Characterization at failure locations can be used to give an indication of the process involved in failure.
- Characterization prior to installation can be used to choose appropriate asset materials and/or protection.

## F69.6 Limitations

- As samples are small, tests only give parameters for a small area, which may or may not be representative of the area of interest.
- Analyzes often needs to be conducted in a lab and can be expensive.
- Correlation between measured parameters and desired result is not always reliable.
- Moisture content of soil sample may not be that seen at the asset location due to variations in factors such as compaction.

**Table F-71. Summary Soil Characterization.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Environmental survey (pipeline assets). |
| | Material type | Soil characterization can be related to any material depending on tests conducted. |
| | Service area | Potable and wastewater. |
| | Access requirements | Access to soil at point of interest. |
| | Limitations relating to asset condition | None. |
| | Continuous/discrete | Results are discreet. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection does not affect assets. |
| Technical suitability | Assessment parameters | Soil parameters. |
| | Integration with software tools | None. |
| | Commercialization of tool | Equipment is widely available, although most tests need to be conducted in a lab. |
| | Previous/existing use of the tool in sector | Wide use. |
| | Accuracy/reliability | Results should be viewed as a qualitative assessment of the general soil properties. |
| | Integration with software tools | None. |
| | Ease of validation of results | Results can be validated through other tests. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Operator training is required; the level is dependant on testing being conducted. |
| | Technology required (level of tool sophistication) | Specialized equipment required for most tests. |
| | Documentation | Techniques described well in literature and standards. |
| | Availability of technical support | Information available in literature and for contractors supplying the services. |

| | Criteria | Assessment |
|---|---|---|
| Economic factors | Cost per inspection | Cost depends on number and type parameters being tested. |
| | Resource requirements | Resources required is dependant on testing being conducted. |

## F69.7 Bibliography


1. Agri-facts: Practical Information for Alberta's Agriculture Industry, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex3684/$file/534-1.pdf?OpenElement , accessed 2005
2. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
3. Heathcote, M. and Nicholas, D. *Life Assessment of Large Cast Iron Watermains*, Urban Water Research Association of Australia, Research Report No 146, 1998
4. Matti, M.A. and A. Al-Adeebt *Sulphate attack on asbestos pipes*, The international journal of cement composites and lightweight concrete, 1985
5. Randall-Smith, M., Russell, A. and Oliphant, R. *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992

## F70.0 Soil Corrosivity

### F70.1 Overview

The predominant deterioration mechanism for ferrous pipes is electro-chemical corrosion. Soil corrosivity tests use one or more soil characteristics to predict the likely rate of corrosion.

A soil's corrosivity to ferrous pipe materials can be assessed in different ways; some methods predict only that corrosion is likely, while others predict a likely rate of corrosion.

### F70.2 Main Principles

Najjaran (2006) reports several different methods that incorporate multiple soil characteristics:

- ***The 10- point DIPRA method*** uses soil resistivity, pH, redox potential, sulfide content and moisture content to classify soils as either corrosive or non-corrosive.
- ***The Metalogic method*** uses twelve soil factors; soil type, soil resistivity, water content, pH, buffering capacity, chloride and sulfide concentrations, ground water level, horizontal and vertical homogeneities and electro-chemical potential to rate corrosivity at four levels from highly corrosive to virtually non-corrosive.
- ***The Spickelmire method*** uses a twenty-five point method and includes soil properties as in the DIPRA method and pipe factors such as pipe location, size, maximum surge pressure, design life, and leak repair difficulty. This method ranked corrosivity at four levels from mild to severe.
- ***Linear Polarization Resistance*** (LPR) is a soil characteristic used to predict the corrosion rate of buried ferrous assets. LPR has a negative correlation with corrosion rate in ferrous assets, meaning that soils with high LPR values will exhibit low corrosion rates. Heathcote and Nicholas (1998) reported that LPR (Also see LPR review) showed significant correlation with pitting rate of cast iron when measured manually.

### F70.3 Application

Soil corrosivity gives an indication of the likelihood that corrosion will occur. It can generally be used to qualitatively rank soil types, such as on a scale from non-corrosive through to very corrosive. Soil corrosivity tests are relevant for buried ferrous assets. Soils can be categorized into broad corrosivity categories that identify areas where corrosion potential is highest.

### F70.4 Practical considerations

- LPR measure using automated systems showed very limited correlation with corrosion rate and so should not be used unless technique correlations to pit rate have been improved.
- Methods for measurement of soil characteristics, such as pH, resistivity, redox potential and moisture content, are available either from standards or literature. Companies are available to conduct all of the required soil characterization work if needed.
- Prediction of pipe condition requires additional information such as pipe age and wall thickness.

## F70.5 Advantages

- Techniques used in predicting soil corrosivity can be conducted prior to laying pipe allowing appropriate corrosion control measures to be undertaken. Categorization of soil types into corrosivity classes can be useful in focusing attention on assets where more detailed monitoring and inspection of buried ferrous assets may be justified.
- Outputs from soil corrosivity tests can be linked to soil layers within a geographic information system, in order to provide a spatial overview of likely areas of high corrosivity.

## F70.6 Limitations

- Most techniques only indicate the corrosion rate qualitatively.
- Corrosion rate does not allow the condition of an asset to be assed on the rate of its degradation.

**Table F-72. Summary Soil Corrosivity.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Environmental survey (pipeline assets). |
| | Material type | N/A |
| | Service Area | Potable and wastewater. |
| | Access requirements | Access to soil required. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Results are discreet. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection does not affect assets. |
| Technical suitability | Assessment parameters | Technique predicts corrosion from soil characteristics. |
| | Integration with software tools | Knowledge of corrosion rate requires knowledge of pipe wall thickness and age in order to provide pipe condition information. |
| | Commercialization of tool | Approaches to soil corrosion assessment are available from commercial suppliers. |
| | Previous/existing use of the tool in sector | Widely used. |
| | Accuracy/reliability | Qualitative assessments. |
| | Ease of validation of results | Results can be validated through inspection of pipes. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Operator training is required. |
| | Technology required (level of tool sophistication) | Lab based testing procedures. |
| | Documentation | Information available from literature. |
| | Availability of technical support | Information available in literature. |
| Economic factors | Cost per inspection | Cost varies depending on technique employed |
| | Resource requirements | Dependent on technique applied |

## F70.7 Bibliography

1. Najjaran, Homayoun; Sadiq, Rehan; Rajani, and Balvant *Fuzzy Expert System to Assess Corrosion of Cast/Ductile Iron Pipes from Backfill Properties*, Computer–Aided Civil and Infrastructure Engineering, **21**, 1, pp. 67-77, 2006
2. Sadiq, R., Rajani, B. and Kleiner, Y. *Fuzzy-Based Method to Evaluate Soil Corrosivity for Prediction of Water Main Deterioration*, Journal of Infrastructure Systems, **10**, 4, pp. 149 – 156, 2004

## F71.0 Soil (Electrical) Resistivity

### F71.1 Overview of Inspection Tool

The predominant deterioration mechanism for ferrous pipes is electro-chemical corrosion. Soils with low resistivity are more likely to have high corrosion rates, while high resistivities are likely to indicate low corrosion rates. As such, measuring soil resistivity gives an indication of the rate at which corrosion will occur. Soil resistivity can be measured in situ or in the lab using a number of techniques.

### F71.2 Main Principles

A number of factors influence the rate at which corrosion of ferrous assets will occur including resistivity, pH, redox potential, moisture content and sulfide levels. Of these factors soil resistivity is considered to be most representative of the likelihood of corrosion (Najjaran et al, 2006). Resistivity varies with changes in soil moisture and salt content, lower moisture content resulting in higher resistivity; lower salt content resulting in higher resistivity.

Field measurements of soil resistivity are conducted using the Wenner technique. This involves inserting four equally spaced electrodes into the soil. An electrical potential is then impressed between the outermost electrodes, and the potential drop between the two central electrodes measured. Several measurements are taken and used to calculate the soil resistivity (Lillie et al, 2004).

Lillie et al (2004) state that the electrodes should be located directly above the pipe and along its axis; however other sources (ASTM G57-95a (2001); TM 5-811-7, 2005) indicate that electrodes should be placed perpendicular to the axis of the pipe.

The Wenner technique measures the average resistivity from the soil surface to a depth equal to the pin spacing, in particular the spacing between the two central electrodes, so this distance should be chosen to coincide with pipe depth.

Lab measurements of soil resistivity can be conducted using a variation of the Wenner technique (G57-95a (2001), AS 1289.4.4.1 -1997) or a two electrode method (ASTM G187-05)

### F71.3 Application

Soil resistivity is an environmental indicator of the corrosivity of soils. In conjunction with other environmental information, the corrosion rate of materials in the soil can be estimated. Reference standards include:

- AS 1289.4.4.1 -1997: Determination of the electrical resistivity of soil.
- ASTM G187-05 Standard Test Method for Measurement of Soil Resistivity Using the Two-Electrode Soil Box Method.
- ASTM G57-95a(2001) Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method.

### F71.4 Practical considerations

- These techniques are widely used in the sector, and services are provided by a number of companies.
- As resistivity can change with depth due to the effect of the water table, when using the Wenner technique, the spacing between each pin should be equal or greater than the pipe depth.

- Measurements should be taken to the side of the line of the pipe, to avoid the pipe from being included in the conduction path.
- Due to differences in the degree of compaction, the results obtained in the laboratory tend to be lower than the corresponding values measured in situ.
- Soil resistivity should not be measured on soil at below-freezing temperatures (TM 5-811-7, 2005).

## F71.5 Advantages

- Low cost technique.
- Gives an indication of soil corrosion potential.
- Widely used technique.

## F71.6 Limitations

- Soil resistivity is only indicative of corrosion rate for buried ferrous assets; further detailed analysis is required to actually determine corrosion rate and asset condition.

**Table F-73. Summary Soil (Electrical) Resistivity.**

| | **Criteria** | **Assessment** |
|---|---|---|
| Technical selection | Assets covered | Environmental survey (pipeline assets). |
| | Material type | Soil. |
| | Service Area | Potable and wastewater. |
| | Access requirements | Access to soil surface required. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Results are discreet. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection does not affect assets. |
| Technical suitability | Assessment parameters | Soil electrical resistivity. |
| | Integration with software tools | None. |
| | Commercialization of tool | Equipment is widely available but generally superseded. |
| | Previous/existing use of the tool in sector | Widespread use. |
| | Accuracy/reliability | Quantitative, but qualitative interpretation. |
| | Ease of validation of results | Results can be validated though other soil test. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Operator training is required. |
| | Technology required (level of tool sophistication) | Low level technological requirements, specialized equipment required. |
| | Documentation | AS 1289.4.4.1 -1997, ASTM G187-05, ASTM G57-95a(2001). |
| | Availability of technical support | Information available in literature. |
| Economic factors | Cost per inspection | Low cost . |
| | Resource requirements | Measurements can be undertaken by a single person. |

## F71.7 Bibliography


1. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
2. Lillie, K., Reed, C. and Rodgers, M. A. R., 2004, *Workshop on Condition Assessment Inspection Devices for Water Transmission Mains*, AwwaRF, USA, 2004
3. Najjaran, H., Sadiq, R. and Rajani, B. *Fuzzy Expert System to Assess Corrosion of Cast/Ductile Iron Pipes from Backfill Properties*, Computer-Aided Civil and Infrastructure Engineering, 21, pp 67-77, 2006
4. Randall-Smith, M., Russell, A. and Oliphant, R., *Guidance manual for the structural condition assessment of trunk mains*, WRc, UK, 1992

# F72.0 Thermographic Testing

## F72.1 Overview

Thermographic testing uses infrared (IR) imagery to locate defects and potential failures in electrical equipment by scanning for thermal abnormalities. As IR energy is emitted from objects due to their thermal properties, thermographic testing enables the early detection of electrical problems that are associated with a thermal signal, such as overheating. This non-destructive test allows for the early identification and repair of defects before they potentially cause unscheduled power losses, equipment damage, or even catastrophic equipment failures.

## F72.2 Main Principles

Thermographic testing detects thermal properties using IR imaging. IR imaging allows invisible IR radiation to be converted into a visible image so that objects are viewed on the basis of their heat emissions rather than light properties. Images can be instantaneously viewed, photographed, video recorded or if required can be downloaded to provide reports and historical records for future comparison. By locating thermal abnormalities in images, such as hot or cold spots, deteriorating and defective components can be identified and repaired or replaced before failure.

## F72.3 Application

Thermographic testing is an effective method of locating problems in all electrical equipment that carries a current. Thermographic testing is potentially applicable to the following: Substations, Switchgear, Motor Control Centers, Motors, Bearings, Transformers, Circuit Breakers, Cables, Terminators, Bus Bars, Bus Plugs, Overhead Distribution Lines, Starters Contactors, Transmission Lines, Power Panels, Lighting Panels, High Voltage Equipment, Switches, Controls and Low Voltage Equipment. IR can also be used for roads and roofs.

- ASTM-E1934-99a and ISO/DIS 18436-8 are applicable to thermographic testing. ISO/DIS 18436-8 is a Draft International Standard (DIS) with no specific standard for this test method.

## F72.4 Practical Considerations

- Thermographic testing is widely applied for the testing of electrical systems; there are numerous commercial organizations that provide specialist skills.
- The testing equipment consists of handheld camera that is battery powered, so it is readily portable.
- Thermographic testing allows rapid scanning of electrical equipment and the results are repeatable. The equipment must be under load conditions during testing.
- Comparison of images taken from regular thermographic testing may show changes in heat emissions, which enables early detection of possible faults.

## F72.5 Advantages

- Thermographic testing allows rapid scanning of equipment and can be used at a distance, meaning that no direct contact or intrusion is required.
- The results are reliable, can be recorded in different formats and sensors can be sensitive to 0.1 °C.

## F72.6 Limitations

- A temperature difference is required to identify electrical faults. Some operator experience is necessary as sensitivity and resolution can be reduced with distance to object and angle of view.
- As most thermographic testing is performed on "live front" energized equipment precautions must be taken to ensure no direct contact with live parts.

**Table F-74 Summary Thermographic Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Wastewater/water electrical infrastructure - substations, switchgear, motor control centers, motors, bearings, transformers, circuit breakers, cables, terminators, bus bars, bus plugs, overhead distribution lines, starters contactors, transmission lines, power panels, lighting panels, high voltage equipment, switches, controls and low voltage equipment. |
| | Material type | N/A |
| | Service area | Potable and wastewater. |
| | Access requirements | Hand held battery operated. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Equipment is required to be on-line/under load. |
| Technical suitability | Assessment parameters | Heat generated. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Commercialized, can be used off the shelf. |
| | Previous/existing use of the tool in sector | Standard industry practice. |
| | Accuracy/reliability | Qualitative. |
| | Ease of validation of results | Direct observation. |
| Utility technical capacity | Asset management sophistication required | Generic approach |
| | Skills required (level of tool sophistication); usability | Field service engineer, HV authorized (in HV areas) |
| | Technology required (level of tool sophistication) | None, is a stand alone portable tool |
| | Documentation | Is well documented. ISO/DIS 18436-8; ASTM-E1934-99a |
| | Availability of technical support | Sufficient suppliers of equipment, training and services. |
| Economic factors | Cost per inspection | Low. |
| | Resource requirements | One operator needed. |

## F72.7 Bibliography


1. ISO/DIS 18436-8: Condition monitoring and diagnostics of machines - Requirements for training and certification of personnel - Part 8: Thermography (Under Development)
2. ASTM-E1934-99a (2005) Standard Guide for Examining Electrical and Mechanical Equipment with Infrared Thermography

# F73.0 Transformer Circuit Protection Coordination and Protection Relays

## F73.1 Overview of Tool

Transformer circuit protection coordination and protection relays are designed to prevent damage to valuable electrical equipment from short circuits or other faults. Coordination of protection relays aims to minimize disruption to network operations by ensuring that only equipment impacted by the fault is isolated and shutdown.

This review outlines the testing and analysis of electrical protection systems that should be undertaken to ensure adequate protection and the reliable performance of protection relays. This type of protective device co-ordination review should be done as part of any comprehensive maintenance program at least every five years.

## F73.2 Main Principles

Coordination of relay protection is designed to ensure that only the equipment threatened with damage is isolated and removed from service. Relay settings determine when a relay sends a control signal to a circuit breaker. A review of transformer circuit protection coordination and protection relays should include analysis of fault levels, equipment ratings, protection installed and protection settings to ensure faults such as short circuits will not cause damage to electrical equipment.

Tests are designed to provide inputs to relay protections that simulate faults, such as short circuits. Tests include primary and secondary injection tests sets for HV/MV distribution switchboards and motor control centers for establishing the protection operates at the right settings and includes motor protection relays. Primary injection testing involves injecting a high current on the primary side of the transformer, which means the whole system is covered by the test and requires the equipment to be off-line. Secondary testing involves disconnecting protective relays from the transformers and circuit breakers, with current and voltage fed directly to relay protection, which means that equipment can stay on-line. Primary injection testing is generally only used in the case where new equipment is being commissioned or when secondary circuits are not accessible.

## F73.3 Application

Analysis of circuit protection coordination and protection relays can be applied to the following: LV switchboards, HV switchgear, transformers and cabling. Relevant standards include:

- AS/NZ 3000 wiring rules. Various standards for equipment types (fuses, breakers, MCCBs, etc.).
- AS 3851-1991: The calculation of short-circuit currents in three-phase alternating current systems.
- AS 3865-1991: Calculation of the effects of short-circuit currents.
- IEC 60865- Short-circuit currents - calculation of effects.
- IEC 60909- Short-circuit currents in three-phase alternating current systems.

## F73.4 Practical Considerations

- Testing of electrical protective systems is standard, particularly in organizations such as power and water utilities.

- The analysis of relay protection and coordination requires an experienced and specialist engineer. There are a number of companies that specialize in providing the expertise to design and test electrical protection systems.

## F73.5 Advantages

- The design and testing of electrical protection systems is critical in preventing damage to important and expensive electrical equipment.
- If adequate information is available there is the potential for non-invasive desktop study of electrical protection systems.

## F73.6 Limitations

- If data on the electrical protection system is lacking, a desktop analysis is not possible. Therefore, direct access to components may required, which in some cases will result in power shutdowns. Plant has to be off-line to enable the tripping of breakers.

**Table F-75. Summary Transformer Circuit Protection Coordination and Protection Relays.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Electrical protection systems; fuses, overload units, CTS, protection relays. |
| | Material type | N/A |
| | Service area | Potable and wastewater. |
| | Access requirements | Access to HV authorized areas. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Gives time co-ordination with other devices for fault currents. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | For testing of equipment reaction it is necessary to trip feeder units with resultant power outages. |
| Technical suitability | Assessment parameters | Time for protection system to react and its interaction with other protection devices. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Fully developed. |
| | Previous/existing use of the tool in sector | Standard industry practice. |
| | Accuracy/reliability | Within tolerances of supplied equipment e.g., tripping times may have a 10% margin. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Requires experienced and qualified engineer. |
| | Technology required (level of tool sophistication) | N/A |
| | Documentation | Standard design in accordance with AS/NZ 3000; AS 3851-1991: AS 3865-1991 ; IEC 60865 ; IEC 60909. |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | N/A |
| | Resource requirements | Site survey and offsite desktop study. |

## F73.7 Bibliography


1. AS/NZS 3000:2000 Electrical installations (known as the Australian/New Zealand Wiring Rules)
2. AS 3851-1991 : The calculation of short-circuit currents in three-phase alternating current systems
3. AS 3865-1991 : Calculation of the effects of short-circuit currents
4. IEC 60865- Short-circuit currents - Calculation of effects - Part 1: Definitions and calculation methods
5. IEC 60909- Short-circuit currents in three-phase AC systems - Part 3: Currents during two separate simultaneous line-to-earth short circuits and partial short-circuit currents flowing through earth
6. Thorp, J.S. *The Protection System in Bulk Power Networks*, Power System Engineering Research Centre, 2003

## F74.0 Transient Earth Voltage (TEV)

### F74.1 Overview of Tool

The detection of transient earth voltage (TEV) is an indicator of partial discharge. In general terms, partial discharge is a minute electrical pulse or discharge occurring in a gas filled void or on a dielectric surface of a solid or liquid insulation system. This can occur upon insulation breakdown due to aging, damage or contamination. The pulse or discharge only partially bridges the gap between the phase to ground insulation. This is an early indicator of insulation failure. Emissions from a partial discharge are electromagnetic, radio up to 80 MHz, light, heat, acoustic ultrasonic and gases.

### F74.2 Main Principles

If a partial discharge occurs in the phase to earth insulation of an item of high voltage plant, a small quantity of charge is transferred capacitively to the earthed metal cladding. An electromagnetic wave is generated at the discharge site which propagates away in all directions. By escaping through an opening in the metal cladding, such as a gasketed joint, this can be detected on the outer surface as a TEV. The TEV has a nanosecond rise time and amplitude that varies widely from millivolts to volts.

### F74.3 Application

TEV can be used to inspect HV switchgear, transformer cable boxes and tappings for the detection of electrical insulation breakdown.

### F74.4 Practical Considerations

- Inspection of HV switchgear is best carried out in conjunction with ultrasonic emission inspection to detect problems between phases, terminations and switch tank spouts (see Ultrasound Emissions review).
- HV authorized personnel only to undertake testing of HV electrical equipment.

### F74.5 Advantages

- TEV is non-destructive and components are monitored while in normal operation.
- This method is easy to use and provides instantaneous information. It is a compact and user-friendly tool that is also very durable.
- There is no requirement to expose electrical live parts. No requirement for directs contact.

### F74.6 Limitations

- Detects discharges to earth through voids or insulation breakdown. It does not detect discharge between phases or into air. It therefore cannot, on its own, be used for all HV switchgear or fault applications.
- It is best used in a device that uses a combination of ultrasound and electromagnetic detection.

**Table F-76. Summary Transient Earth Voltage (TEV).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | HV switchgear, transformer cable boxes and tapping selector switches. |
| | Material type | Electrical insulation. |
| | Service area | Potable and wastewater. |
| | Access requirements | HV authorized person usually required to access plant areas. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Continuous during test. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | On-line |
| Technical suitability | Assessment parameters | Electrical discharge to earth. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Commercialized, can be used off the shelf. |
| | Previous/existing use of the tool in sector | Industry standard practice. |
| | Accuracy/reliability | Validity confirmed on insulation testing of unit (requires power down) and physical inspection. Is an indicative tool. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Field service engineer, HV authorized. |
| | Technology required (level of tool sophistication) | None is a stand alone portable tool. |
| | Documentation | Is well documented. |
| | Availability of technical support | N/A |
| Economic factors | Cost per inspection | Low cost test. |
| | Resource requirements | One operator needing only time required to access plant item. |

## F74.7 Bibliography

1. *EA technology*, http://www.eatechnology.com, accessed 2006

## F75.0 Ultrasonic Emission Inspection

### F75.1 Overview of Tool

The use of audible sound has long been part of the information gathering process to diagnose the operating condition of plant and machinery.

Audible sounds generated by individual bearings, electrical arcing, or leaks are difficult to differentiate in a noisy environment where components operate within close proximity of one another. Machinery also generates sound above the range of normal human hearing in the ultrasound region. Due to the properties of ultrasound, the sounds made by individual parts can be differentiated. Any physical changes in equipment will produce resultant sound changes. Theses sound changes will often first appear within the ultrasound spectrum before the audible spectrum, giving the opportunity for early diagnosis.

Ultrasonic emission inspection is a non-destructive method for maintenance diagnostics, safety, and quality control.

### F75.2 Main Principles

Machines and equipment generate both audible sound and ultrasound when in operation. Ultrasound is sound that occurs above the normal range of human hearing, the upper range of human hearing is typically 20 kHz. Defects such as electrical arcing and bearing damage can be identified by their ultrasound signature.

Inspection is undertaken using a portable sensor. The ultrasound signal is converted into the audible region with the normal audible signals being filtered out. The reproduced noise retains recognizable characteristics such that a bearing sounds like a bearing and electrical arcing sounds like arcing. This permits detection even in extremely noisy environments.

Ultrasound is very directional and attenuates much faster than audible sound. Therefore it stays close to its source allowing for easier location. Detection can be improved by making direct contact with the plant item using a solid probe so eliminating air gap attenuation.

In the case of bearings and gears, ultrasound will be emitted prior to mechanical failure, thus giving the end-user of the ability to perform maintenance before breakdown occurs.

Ultrasonic emission inspection can also be used to detect and pinpoint electrical arcing, tracking (partial discharge) or corona discharge on high voltage and medium voltage electrical systems.

### F75.3 Application

Ultrasonic emission inspection can be used to inspect plant mechanical defects within motor bearings and gearing. Electrical faults that involve arcing, tracking over insulation (partial discharge) or air discharge (corona) can also be detected. Acoustic ultrasonic can also be used to check steam trap performance and to find air leaks.

- Ultrasonic emission inspection is referenced in ISO-10375 - Non-Destructive Testing - Ultrasonic Inspection - Characterization of Search Unit and Sound Field.

### F75.4 Practical Considerations

- Ultrasonic emission inspection is widely used throughout industry due to ease of use and instantaneous results it obtains.
- Ultrasonic emission detectors are compact, user-friendly and very durable. They can be hand carried. The method can be implemented for routine predictive and preventive

maintenance inspections, for identification of failed components when a problem is suspected, and for confirmation of repairs.

- This method cannot be used in isolation for all HV switchgear applications. Inspection of HV switchgear is best carried out with in conjunction with transient earth voltage inspection (see transient earth voltage review). HV authorized personnel only to undertake testing of HV electrical equipment.

## F75.5 Advantages

- Ultrasonic emission inspection is non-destructive and components are monitored while in normal operation.
- There is no requirement to expose electrical live parts or for direct contact. This method is easy to use and provides instantaneous information.
- This inspection method can be used in hazardous areas with suitably rated detectors.

## F75.6 Limitations

- Ultrasonic's will show problems with air switches, insulators and bushings in outdoor structures only where direct air passage is available, for example, through the skin of the cable box.
- It cannot, on its own, be used for all HV switchgear applications. Inspection of HV switchgear is best carried out with in conjunction with transient earth voltage inspection (see Transient Earth Voltage Review).

**Table F-77. Summary Ultrasonic Emission Inspection.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Wastewater/water motor bearings, HV/ MV switchgear. All components from main switchboards to individual motors. |
| | Material type | N/A |
| | Service area | Potable and wastewater. |
| | Access requirements | No portable battery operated. Physical contact required via probe to outer casing. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Continuous during test. |
| | Destructive/non destructive | Non-destructive test. |
| | Interruption to supply/function | Can be on-line. |
| Technical suitability | Assessment parameters | Mechanical condition, electrical discharges. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Commercialized; can be used off the shelf. |
| | Previous/existing use of the tool in sector | Standard industry practice. |
| | Accuracy/reliability | Indicative measure. |
| | Ease of validation | Requires inspection of asset. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Field service engineer |
| | Technology required (level of tool sophistication) | Tool only. |
| | Documentation | Well documented. ISO-10375. |
| | Availability of technical support | Is well documented. |

| | Criteria | Assessment |
|---|---|---|
| Economic factors | Cost per inspection | Relatively low cost |
| | Resources required | One operator needing only time required to access plant item and listen. |

## F75.7 Bibliography


1. ISO-10375 - Non-Destructive Testing - Ultrasonic Inspection - Characterisation of Search Unit and Sound Field
2. CTRL, http://www.ctrlsys.com/library/faq/faq_ut.php, accessed 2006
3. EA technology, http://www.eatechnology.com, accessed 2006

## F76.0 Ultrasonic Measurements; Continuous (Guided Wave)

### F76.1 Overview

Ultrasonic inspection is a non-destructive test conducted by sending high frequency sound into an asset and evaluating any echoes detected. Ultrasonic examination procedures are widely used for thickness measurement, corrosion monitoring, delamination checks and flaw detection in welds, forgings, castings and pipes.

In the material, the ultrasonic pulses travel in straight lines, until they hit an interface between two different materials (steel and air for example), or a flaw, when most of the energy of the vibration will be reflected. A small amount of the energy is reflected back to the probe, where it is detected.

This section applies to continuous techniques used for the rapid screening of pipes for corrosion/erosion. Discrete ultrasonic inspection techniques are considered in a separate section (see Ultrasonic Measurements; Discrete).

### F76.2 Main Principles

In recent years much work has gone into the development of ultrasonic techniques for the rapid screening of pipes for corrosion/erosion. This has resulted in systems that make use of low frequency guided waves. Systems were originally designed for use on above-ground exposed or insulated pipes, but are now used on buried pipes, though the range of inspection can be shorter.

Depending on the type of guided wave used, the number of transducers can range between two and four. Torsion waves require only two transducers, while longitudinal waves required three or four transducers. Torsion wave systems were first introduced in 1998 and can be used in pipes filled with water. Longitudinal waves are not used for water filled pipes as the signal is partially propagated through the water and also reenters the pipe wall, making signal interpretation very difficult even in simple situations. Longitudinal systems that use three transducers can only operate on a single frequency, while four transducer systems can operate using more frequencies, improving results.

During testing a unit using piezoelectric transducers is clamped around the pipe and ultrasound is sent simultaneously in both directions along the pipe. The signal obtained is similar to a conventional ultrasonic A-scan, where the horizontal axis represents distance along the pipe and the vertical axis represents signal amplitude, which is indicative of the severity of the corrosion. Unlike conventional A-scans, the signals are displayed from three different wave modes, namely symmetrical, horizontal flexural and vertical flexural. The relative intensities and characteristics of these three signals are important in identifying different distributions of corrosion.

Electro-magnetic acoustic transducers (EMATs) have also been used in some applications. EMATS give relatively consistent results in comparison to piezoelectric transducers since they do not need any couplant. Other methods are available which do not require direct contact with the pipe, however these techniques suffer from increased noise in the signal, reducing accuracy and the length of pipe which can be inspected.

### F76.3 Application

Continuous ultrasonic measurement is used to obtain an understanding of corrosion along a pipeline, above and below ground pipes can be assed. This technique is suitable for use on pipe diameters above 50mm (2.0") and on wall thicknesses up to 40mm (1.6").

- ASTM E1816-96(2002); Standard Practice for Ultrasonic Examinations Using Electromagnetic Acoustic Transducer (EMAT) Techniques.

## F76.4 Practical considerations

- While this technique is relatively new, commercialized tools and services are available, although generally from specialized consulting companies.
- Recent advances in these systems allow focused guided waves to be used. These allow the location of circumferential corrosion and improved signal to noise ratio. Although propagation distances vary according to pipe geometry, contents, coating/insulation and general condition, it is not unusual that a range of up to 30m (100') in either direction from the transducer can be inspected. The technique is equally sensitive to internal and external corrosion, but cannot distinguish between them.

## F76.5 Advantages

- The principal advantage of this technique is that it provides 100% initial screening coverage, and only requires local access to the pipe surface (i.e. exposure of small section of buried pipe or removal of a small amount of insulation) at those positions where the transducer array is to be attached.

## F76.6 Limitations

- Continuous ultrasonic measurement is more expensive than discrete ultrasonic measurements. While the technique is equally sensitive to internal and external corrosion, it cannot distinguish between them.
- Only very limited pipe lengths can be inspected when the pipe is heavily coated in a very alternative material such as fresh bitumen. Surface deposits such as scale and corrosion products also limit the length pipe which can be inspected.

**Table F-78. Summary Ultrasonic Measurements; Continuous (Guided Wave).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, water and wastewater pipeline infrastructure. |
| | Material type | Iron and steel pipes. |
| | Service Area | Waste and potable water. |
| | Access requirements | Direct contact with pipe wall required. |
| | Limitations relating to asset condition | No limitations relating to asset condition provided direct contact with the pipe wall is available. |
| | Limitations relating to asset size/geometry | Pipe diameters above 50mm (2.0") and on wall thicknesses up to 40mm (1.6"). |
| | Continuous/discrete | Continuous readings. |
| | Destructive/non destructive | Non-destructive. External tool require exposure of pipe surface. |
| | Interruption to supply/function | Does not require interruption. |
| Technical suitability | Assessment parameters | Level of wall thickness or corrosion pit depths in iron and steel pipes. |
| | Integration with software tools | Tool integrated with software; some systems upload results via mobile phones. |
| | Commercialization of tool | Commercialized. |
| | Previous/existing use of the tool in sector | Some use reported in the literature. |
| | Accuracy/reliability | Quantitative. |

| | Criteria | Assessment |
|---|---|---|
| | Ease of validation of results | Validation possible only by comparison with manual /direct measurements. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); useability | Professional skills to interpret output data. Tool operation typically by a trained technician. |
| | Technology required (level of tool sophistication) | Specialized equipment and dedicated computer software. |
| | Documentation | Tool principles and description of reports generated by tool will be available. |
| | Availability of technical support | Service provided by special operator. |
| Economic factors | Cost per inspection | Variable. Staff time will be the highest cost. Equipment cost US$1,000-10,000. |
| | Resource requirements | Typically one person. |

## F76.7 Bibliography


1. Lowe M.J.S., Alleyne D.N., Cawley P., *Defect detection in pipes using guided waves*, Ultrasonics Vol. 36, p147-154, Elsevier Science, 1998
2. Wassink, C.H.P., Robers M.A., de Raad J.A, and Bouma T. (2000) *Condition Monitoring of Inaccessible Piping*, 15th World Conference on Nondestructive Testing, Roma (Italy) 15-21 October 2000. Accessible at: http://www.ndt.net/article/wcndt00/papers/idn075/idn075.htm

## F77.0 Ultrasonic Measurements; Discrete

### F77.1 Overview

Ultrasonic inspection is a non-destructive test conducted by sending high frequency sound into an asset and evaluating any echoes detected. Ultrasonic examination procedures are widely used for thickness measurement, corrosion monitoring, delamination checks and flaw detection in welds, forgings, castings and ferrous pipes.

An ultrasonic flaw detector has an oscillator circuit that sends electrical pulses to a probe. The transducer in the probe produces ultrasonic vibrations when it receives the electrical pulse. A range of vibration frequencies can be chosen between 1 MHz and 15 MHz depending on the specific application. For example, typical frequencies used in weld examination are between 2 MHz and 5 MHz.

The ultrasonic vibrations leave the probe and are conducted into the material to be tested by a couplant, usually grease, oil, water, paste or gelatin.

In the material, the ultrasonic pulses travel in straight lines, until they hit an interface between two different materials (steel and air for example), or a flaw, when most of the energy of the vibration will be reflected. A small amount of the energy is reflected back to the probe, where it vibrates the piezoelectric crystal, generating an electric current. This current returns to the flaw detector, where it is amplified, rectified, filtered and displayed.

This section applies to discrete techniques used for screening of pipes for corrosion/erosion at discrete locations. Continuous ultrasonic inspection techniques are considered in a separate section.

### F77.2 Main Principles

Several methods are available to produce the ultrasonic signals, piezoelectric ceramics being the most common. Other methods include electromagnetic acoustic transducers (EMATs), magnetosctrictive sensors (MSS), lasers and piezoelectric polymers.

When measuring wall thickness, the crystal is aligned perpendicular to the wall. The waves propagate to the back wall and are reflected back towards the transducer. The transit time from initial pulse to reception of back wall reflection is recorded. Knowledge of the material's ultrasonic velocity then gives the distance traveled by the wave. Calibration targets of known thicknesses and materials are normally used to make these determinations

Figure F-12 illustrates a simple set-up using the pulse-echo principle and a twin crystal probe. In this configuration, one crystal acts as transmitter and the other as the receiver.

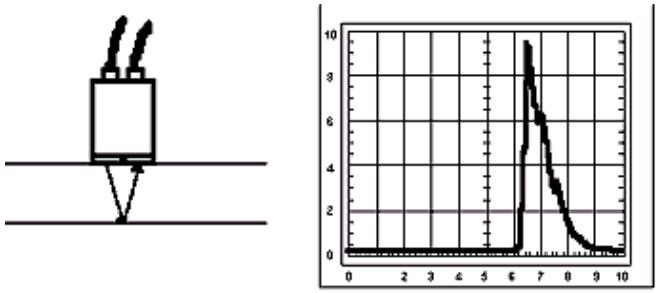


**Figure F-12. Simple Set-Up Using the Pulse-Echo Principle and a Twin Crystal Probe. (Reprinted with permission from: Drury, J., 1996)**

Figure F-13 shows a more complicated situation where the ultrasonic signal passes through three materials the cement lining, pipe wall and corrosion products respectively. Four

echo signals are generated in this case, at the air-cement lining, cement lining-pipe wall, pipe wall corrosion products and corrosion products-air interfaces. It should be noted that the situation below is a schematic only, the transducer and detector both need to be in contact with the surface of the asset being inspected. Also field experience indicates that ultrasonic techniques are unable to detect flaws in cement mortar linings.

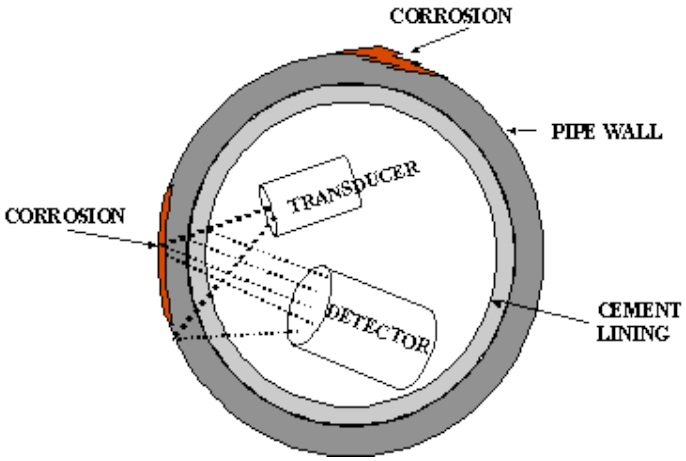


**Figure F-13. Multiple Interfaces on Cement-Lined Water Pipe Create Multiple Ultrasonic Reflections (Shown with a Probe Located Internally).**

Wall thickness measurements are performed using a conventional flaw detector and a compression wave probe, which sends longitudinal waves into the component at normal incidence to the surface. Signals are displayed on the flaw detector screen in the form of an A-scan, in which the horizontal axis represents time and the vertical axis represents signal amplitude. When a 0° compression probe is being used, the horizontal axis is equivalent to the depth of the discontinuity (flaw or other interface) from the scanning surface.

The use of an A-scan display allows the operator to distinguish more easily between signals originating from embedded plate flaws and the nominal back wall response. Also, the dynamics of the back wall echo can be observed on the A-scan display to detect the presence of pitting.

Conventional twin-crystal 0° compression probes are generally used to detect hidden corrosion. However, where pitted surfaces are being assessed for remaining thickness, pencil probes are used. These have a pointed tip which is designed to fit into the pits, so that the remaining thickness can be measured where pitting is at its most severe.

## F77.3 Application

Use for thickness measurement, corrosion monitoring, delamination checks and flaw detection in welds, forgings, castings and ferrous pipes.

- ASTM E1816-96(2002); Standard Practice for Ultrasonic Examinations Using Electromagnetic Acoustic Transducer (EMAT) Techniques.

## F77.4 Practical considerations

- The technique is fully commercialized, with widespread use of the probes reported in literature and trade journals. Accuracy of results can be high, but depends upon application and calibration.
- When ultrasonic tools are used for condition assessment, the ideal reflector of the ultrasonic sound energy is a flat, smooth, surface parallel to the scanning surface and

larger in area than the beam at that range. These characteristics are not found in corroded pipes.

- An eroded pipe surface with a gradual gradient over most of the length of the eroded area is a reasonable reflector (the surfaces are nearly parallel and relatively smooth). An ultrasonic probe placed anywhere in the eroded region is therefore likely to give a reasonable echo amplitude. Reasonable measurement accuracy can be expected as long as the beam circumference is smaller than the eroded area. Drury (1996) showed that in most cases corrosion measurements are accurate to within 0.5mm. If, however, the erosion is uneven and with corrosion pits the accuracy is limited. Corrosion pits can have a variety of shapes, but may be generalized into two forms, lake type and cone type (Drury, 1996).

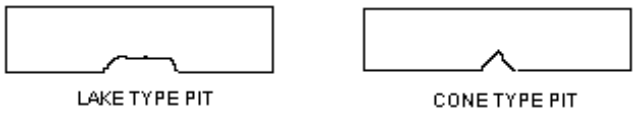


**Figure F-14. Types of Corrosion Pits.**

- In lake type pitting the major part of the reflecting target is relatively parallel to the scanning surface and will give adequate echo amplitude, provided the ultrasonic probe is placed over the "flat" region.
- Cone type pits are the most difficult to detect as the major reflecting surfaces are not favorably orientated, the surfaces are rough and often ridged, and the target area is often small in relation to the beam cross section. The latter is true particularly of the base of the pit. For this reason cone type pits are the least likely to be detected and have the greatest inherent inaccuracy in their measurement.
- The likelihood of detecting corrosion pitting using the ultrasonic method is dependent on many factors. Until recently, it was common practice to use spot checks on a grid pattern. Area scanning is however now preferred and can be applied manually using contact scanning or via automated scanning.
- As noted above, the reflecting surface that is offered by typical corrosion pitting is often poor for ultrasonic purposes and the operator needs to be able to see the character of the signal to avoid errors. For this reason simple digital thickness meters are not suitable for corrosion detection. Equipment with an A-Scan presentation is preferred and this can be complimented by B-Scan (through wall view) and C-Scan (plan view image) facilities.
- The curved outer surface of pipe causes the incident ultrasonic beam to diverge. The effect becomes more severe as the diameter of the pipe decreases. The effect is overcome by making the circumferential dimension of the beam focus on the surface of the test material small compared with the diameter of the pipe being inspected. For this reason, probes with small beam focus are more suited for small diameter pipe.

## F77.5 Advantages

- Probes are availability in wide a range of sizes, measurement accuracies and costs.
- Simple to use. User manuals supplied with instruments sufficient for operator training.
- The external units can be used without supply interruption.
- Wall thickness reductions detected with a reasonable degree of accuracy.

## F77.6 Limitations

- Inspection requires pipe cleaning prior to inspection to remove material, which would affect the readings. For internal inspection, the pipe has to be off-line and dry as inspection units are generally not waterproof.
- If the pipe is inspected from the inside, care needs to be taken because the surface of the specimen (concave rather than convex) will make the beam converge rather than diverge.

**Table F-79. Summary Ultrasonic Measurements; Discrete.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, tanks, etc. |
| | Material type | Iron and steel. |
| | Service Area | Waste and potable water. |
| | Access requirements | Direct contact with asset wall required. Pipe surface must be clean. The asset surface may also require shot blasting abrading to provide a smooth surface. |
| | Limitations relating to asset condition | Poor coupling on excessively pitted surfaces can cause inaccuracies. |
| | Limitations relating to asset size/geometry | Internal tools: generally limited to pipes 250 mm and greater. External tools: no limit, but small diameter pipes require probes with small footprint to minimize curve effect. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Non-destructive. External tool require exposure of pipe surface. Internal tool requires access by cut-ins or other methods. |
| | Interruption to supply/function | External tool does not require interruption. Internal tool application requires pipe to be off-line. |
| Technical suitability | Assessment parameters | Wall thickness or corrosion pit depths in iron and steel pipes. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Commercialized, availability widespread. |
| | Previous/existing use of the tool in sector | Widespread commercial use of the UT probes reported in literature and trade journals. |
| | Accuracy/reliability | Quantitative. |
| | Ease of validation of results | Validation possible only by comparison with manual/direct measurements. Calibration of tool against reference samples required. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); useability | Tool operation typically by a trained technician. User manual sufficient for operator training. |
| | Technology required (level of tool sophistication) | Specialized equipment and dedicated computer. software. |
| | Documentation | Tool principles and description of reports generated by tool will be available |
| | Availability of technical support | Service provided by special operator. |
| Economic factors | Cost per inspection | Variable. Staff time will be the highest cost. Equipment cost US$1,000-10,000. |
| | Resource requirements | Typically one person to carry out test, but pipe must be excavated. |

## F77.7 Bibliography


1. Drury, J.C. *Corrosion monitoring and thickness measurements – what are we wrong?,* IIR Bulk Liquid Storage Tank Conference London 22nd /23rd January 1996, accessed at: http://www.silverwinguk.com/en/technical%20pdfs/ultrasonics_corrosion_pitting.pdf
2. Saka, M. and Salam Akanda, M. A. *Ultrasonic Measurement of the Crack Depth and the Crack Opening Stress Intensity Factor under a No Load Condition*, Journal of Nondestructive Evaluation, Vol. 23, No. 2, pp 49-63, 2004

## F78.0 UtilNets

### F78.1 Overview

UtilNets is a prototype software-based decision-support system intended to help manage the preventative maintenance of water distribution assets. It performs current condition assessments and reliability-based life predictions for pipes, and analyzes the consequences of maintenance decisions.

UtilNets uses a GIS-based user interface, and results are presented as thematic maps and tables. The tool provides a forecast on the aggregate structural, hydraulic, water quality, and service reliability of the network, together with an assessment of the required rehabilitation expenditures. It also provides support to rehabilitation planning by ranking each pipe segment in the whole network on a basis of its need for rehabilitation.

Currently, the software is in a prototype phase and can only be used in the assessment of cast-iron water mains.

### F78.2 Main Principles

UtilNets is based on physical models of asset degradation. The life expectancy of pipe segments is determined based on known asset performance data and the permanent, seasonal and variable loads to which a pipe segment is subjected. This life expectancy is then used in conjunction with budgetary figures for the prioritisation of asset rehabilitation measures such as lining or replacement. While still in the prototype phase UtilNets has been implemented for cast-iron water pipes, it is extendable to other pipe materials, and includes the following:

- Probabilistic models that give a measurement of the likelihood of structural, hydraulic, water quality and service failure of pipe segments over the next several years.
- Assessment of both the quantifiable and qualitative consequences of various rehabilitation options, including the ‘do nothing’ option, over time.
- Selection of the optimal rehabilitation policy for each failed pipe segment.
- An aggregate structural, hydraulic, water quality and service profile of the network together with an assessment of the required rehabilitation expenditures.
- An assessment of network reliability in terms of demand point connectivity and flow adequacy.

UtilNets optimizes the individual rehabilitation policy for each segment and the ranking of rehabilitation within the whole network.

### F78.3 Application

The software is designed to facilitate maintenance management of water distribution assets. A prototype of UtilNets has been implemented for cast-iron water pipes, but is extendable to other pipe materials

### F78.4 Practical considerations

- UtilNets has been used by several European water authorities during its development, but is not yet commercialized.
- Since most utilities have in general incomplete information about the state of their pipe network, a complex Default Manager has been incorporated to yield forecasts even

where data is incomplete. Probability curves are provided to assist the Default Manager where applicable.

- A data dictionary has also been prepared as part of UtilNets to assist users. The data dictionary sets out the way in which data is held, by both type and units.

## F78.5 Advantages

- A data dictionary has been prepared as part of UtilNets to assist the user in setting up the system.
- The software comes with an import manager which can be used to import data into the UtilNets database from a number of sources such as Oracle and Access databases, text files and Excel.
- The software provides defaults that allow analysis when there are data gaps.

## F78.6 Limitations

- UtilNets in its current prototype form is rigid, complex and requires large amounts of data that may be unaffordable to collect and to enter on to the system. For this reason more utilities are being involved from across Europe to help the developers in designing the commercially available version of UtilNets.
- Currently only grey and ductile cast-iron water mains can be assessed.

**Table F-80. Summary UtilNets.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, water pipeline infrastructure. |
| | Granularity | Sub system level. |
| | Service Area | Potable. |
| Technical suitability | Focus of analysis | Reliability-based, decision-support system for the maintenance management of pipes. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good asset data is available. |
| | Commercialization | Currently prototype software. |
| | Previous/existing use of the tool | Only been used by several European water authorities during its development. |
| | Ease of validation | Via statistical means only. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Potable only; designed for assessment at a segment level, utilizing a cluster of pipes. |
| | Integration with other tools/GIS | None. |
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management where good asset data is available, though defaults are provided. |
| | In-house skills required | Asset manager/engineer. |
| | Technology required | PC based tool. Windows based system. |
| | Documentation | Only limited documentation available. |
| | Data Requirements | Good quality asset data and asset failure history data is required. |
| | Linking to asset data | No direct link. |
| | Availability of software and technical support | Only limited support available at this time. |
| | Usability | High skill levels may be required. |

## F78.7 Bibliography

1. Hadzilacos, T.; Kalles, D.; Preston, N.; Melbourne, P.; Camarinopoulos, L.; Eimermacher, M.; Kallidromitis, V.; Frondistou-Yannas, S.; and Saegrov, S. *UtilNets: a water mains rehabilitation decision-support system*, Computer, Environment and Urban Systems, Volume: 24, Issue: 3, pp. 215-232, 2000

# F79.0 Valve Exercising

## F79.1 Overview

The operation of valves is critical to the function of a water distribution system. In the event of a pipe failure, valves are used to minimize the impact and to allow repair work to be carried out. Boundary valves can also be operated in an emergency to rezone areas. As such, valve locations should be known and operation checked intermittently, although the impact of the disturbed flow must be considered before doing this (change in flow conditions can disturb sediments and cause discoloration events).

Valve exercising is a non-destructive test used to ensure the function of valves by moving them through their full range of motion. Periodic operation gives a measure of operability, which in turn can be used as an indicator of condition. A valve exercising program is thereby used as a means of identifying faulty or broken valves needing replacement.

## F79.2 Main Principles

Valve exercising is generally performed as a program where all valves in a network are assessed. A valve exercising program consists of four main components; 1) locating the valve, 2) exercising the valve, 3) maintaining up-to-date records for each valve and 4) scheduling repairs as required.

When conducting a valve exercising program, each valve should be operated through a full cycle and returned to its original position on a regular basis. The time frame can vary between authorities, depending on local experience, but should be often enough to prevent a build-up of corrosion products and any other deposits that could render the valve inoperable or prevent full closing. The time interval between valve exercising for more critical valves should be shorter than for other less important valves.

When conducting the program, a detailed record of valves should be maintained including the number of turns required to close or open the valve, torque required to operate valve (if possible), valve location, valve condition, maintenance required etc. This data should be compared with previous records to identify any changes to valve operation.

If when exercising valves the action is tight (requires more torque than previously), the operation should be repeated until the opening and closing actions are smooth and free. Equipment is now widely available to operate valves reducing the effort required by operators.

## F79.3 Application

Valve exercising is conducted in order to maintain an up-to-date record of valve condition, schedule repair work as required and to extend valve life through preventative maintenance. The following documents provide guidance on valve exercising:

- ANSI/AWWA G200-04, Distribution Systems Operation and Management, American Water Works Association
- AWWA Manual M44 Distribution Valves, American Water Works Association

## F79.4 Practical considerations

- Equipment is now widely available to operate valves reducing the effort required by operators, reducing back problems and improving the efficiency of operation.
- A program of flushing may be undertaken first in an attempt to minimize the risk of water quality issues associated with changed flow conditions when valves are operated.

- The torque used to operate a valve should be the lowest required. This torque should be maintained throughout as too much torque on closing will mean significantly more torque will be required to reopen the valve. Too much torque can also force the valve and a higher percentage of broken valves will result.

## F79.5 Advantages

- Valve exercising can increase the lifetime of a valve, removing build-up on the action that can prevent operation.
- Allows valves requiring repair to be identified.

## F79.6 Limitations

- Cost of introducing the program may seem prohibitive to some authorities.
- Changed flow conditions could result in disturbance of sediments and discoloration events.

**Table F-81. Summary Valve Exercising.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Valves. |
| | Material type | N/A |
| | Service Area | Potable. |
| | Access requirements | Valve must be accessible. |
| | Limitations relating to asset condition | No restrictions, if the valve cannot be exercised in its current condition then it should be repaired or replaced. |
| | Limitations relating to asset size/geometry | Depends on equipment being used to operate valve. |
| | Continuous/discrete | Discrete. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection can be conducted on-line. |
| Technical suitability | Assessment parameters | Valve condition and operability. |
| | Integration with software tools | N/A |
| | Commercialization of tool | Equipment for valve exercising is fully commercialized |
| | Previous/existing use of the tool in sector | Not used historically, but is now being undertaken. |
| | Accuracy/reliability | Direct assessment of operability. |
| | Ease of validation of results | N/A |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); useability | Operator needs training in procedure of equipment use and data recording. |
| | Technology required (level of tool sophistication) | Require specific equipment to operate valves, where not operated by hand. |
| | Documentation | Tools and related documentation are available from equipment suppliers. |
| | Availability of technical support | Tool supported from equipment supplier. |
| Economic factors | Cost per inspection | Low cost. |
| | Resource requirements | Requires only single person, equipment to operate valve and to record relevant data. |

## F79.7 Bibliography


1. Blakely, D. *Why bother with a valve exercising program,* On Tap Magazine, National Drinking Water Clearinghouse, 2004
   Accessed October 2006 at: http://www.nesc.wvu.edu/ndwc/articles/OT/WI04/valve.html.
2. Hurley, L. (2005) *Water Main Valve Exercising Program*, Conference Proceedings of Pipes Wagga Wagga 2005, Charles Sturt University, Wagga Wagga, N.S.W., October 17-20, 2005

# F80.0 Vibration Analysis

## F80.1 Overview of Tool

Vibration analysis is used to monitor the condition of assets and for fault diagnosis. Vibration is typically measured using hand-held (can be permanently positioned) accelerometers placed on the equipment at key measurement points, with portable data collectors and software for vibration analysis. Vibration analysis is commonly used on large items of rotating equipment, such as turbines, centrifugal pumps, motors, gearboxes etc.

## F80.2 Main Principles

All machines vibrate; over time the pattern of this vibration changes as the asset condition changes. By measuring the displacement at different points of an asset over time using transducers, the pattern of the vibration can be established.

The pattern of the vibration provides a great deal of information about the asset, such as RMS level (imbalance and misalignment), shock pulse (bearing condition) and spike energy. This information can then be analyzed using Fast Fourier Transform techniques. Once broken down into component frequencies, patterns can be observed that relate to plant operation. An example of this is a fan's rotation with its resultant signature frequencies and the additional frequency caused by an imbalance on one of the blades.

Analysis can be preformed by experience and knowledge of the equipment, manufacturer's guidelines, or by using proprietary software. In the example given above, the number of fan blades and speed will directly relate to observed frequencies so allowing the cause to be determined. A severity number can then be assigned, to act as a benchmark. The number is chosen either by experience or the proprietary software. If the number increases, each time the asset is tested, the condition of the asset has deteriorated. The importance of changes will be different for differing assets. Understanding when to take action requires experience, training, manufacturer's guidance and Standards.

## F80.3 Application

Vibration analysis can be used on any vibrating machinery, but is most commonly used on machinery with rotating parts such as gearboxes, drive shafts, motor bearings, rotors in electric motors, pumps and fans.

The ISO 10816-1:1995 and BS ISO 18436-2:2003: reference vibration analysis.

BS ISO 18436-2:2003 specifies the general training requirements for personnel who perform condition monitoring and diagnostics on assets using vibration analysis. Certification to this standard will provide recognition of the qualifications and competence of individuals to perform machinery vibration measurements and analysis using portable and permanently installed sensors and equipment. However, ISO certification is only necessary if a utility is ISO certified; the Vibration Institute provides various levels of certification from technician to expert and is generally used by most industries in the United States.

## F80.4 Practical Considerations

- Vibration analysis is in wide use throughout manufacturing industry, using both permanent and portable transducers. While it is relatively easy to record vibration data, proper analysis requires experienced and trained personnel.

- Vibration analysis should be used as part of routine assessment to allow for developing trends in the equipment to be identified. Vibration analysis assessments are often carried out on a monthly basis.
- Vibration can be measured using a number of different types of transducers; accelerometers, velocity transducers and displacement transducers. Accelerometers are the most common and versatile transducers in use and the only type capable of measuring high frequency vibration such as that produced by bearing and gear problems. However, accelerometers have reduced accuracy at low frequencies.
- Repeatability is key to worthwhile comparisons. If the plant is operated at different speeds, the frequencies generated and their amplitude may be changed. The plant must therefore be operated in the same manner and the same load as previous samples. During a sample the load and speed must remain constant.
- Block/washers are normally installed on equipment to provide a stable source for the vibration probe and to provide repeatability of results.

## F80.5 Advantages

- Vibration analysis is non-destructive. Portable measuring devices can be used. Assets can remain on-line subject to repeatability issues noted above.

## F80.6 Limitations

- Must form part of a monitoring program to allow comparison with previous results.

**Table F-82. Summary Vibration Analysis**

| | Criteria | Assessment |
|---|---|---|
| Technical Selection | Assets covered | Rotating machinery such as gearboxes, misalignment of couplings on drive shafts, motor bearings, out of balance rotor in electric motors, pumps, and fans. |
| | Material type | N/A |
| | Service area | Potable or wastewater. |
| | Access requirements | Fixed test points required to ensure same measuring point used. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Can be either. More usually discrete measurement. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Must be on-line with same load conditions as previous test. |
| Suitability | Assessment parameters | Vibration. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Fully developed and of the shelf. |
| | Previous/existing use of the tool in sector | Widely used. |
| | Accuracy/reliability | Good accuracy of measurement |
| | Ease of validation of results | Alignment checks, ultrasound measurement. |

| | Criteria | Assessment |
|---|---|---|
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); usability | Requires training. |
| | Technology required (level of tool sophistication) | Standard PC. |
| | Documentation | Well documented. ISO 10816; ISO 18436. |
| | Availability of technical support | Widely available. |
| Economic factors | Cost per inspection | No information. |
| | Resource requirements | One person no more than a few minutes per load once test points are established. |

## F80.7 Bibliography


1. ISO 10816-1:1995: Mechanical vibration -- Evaluation of machine vibration by measurements on non-rotating parts -- Part 1: General guidelines
2. BS ISO 18436-2:2003: Condition monitoring and diagnostics of machines - Requirements for training and certification of personnel
3. *Vibration School.com*, http://www.vibrationschool.com/index.htm, accessed 2006

## F81.0 Visual Inspection (Pipes)

### F81.1 Overview

Visual inspection is a low-tech inspection method of structural condition assessment that requires no specialized equipment and can provide a great deal of useful information about buried assets.

Visual inspection can be carried out as an opportunistic approach to condition assessment when assets are unearthed for operational reasons. Visual inspection is also undertaken as a precursor to other condition assessment techniques.

After exposing the asset, visual observations should be recorded using written descriptions, photography and/or video recordings. Exposing buried assets also allows the quality and condition of back fill to be assessed.

### F81.2 Main Principles

Visual inspection of the external surface of a buried asset requires the asset to be exposed. Once exposed and cleaned, the condition of any external protective measure such as PE sleeving or bitumen coating can be inspected.

The spread and pattern of any deterioration on the asset can then be assessed. This may provide an indication of the cause of the deterioration, and the likelihood of it being more widespread.

Unearthing the asset also allows the quality and condition of backfill to be assessed. The quality and condition of back fill is a critical factor for polymeric pipe lifetime, and can also strongly affect the condition of external coatings on ferrous mains. In particular:

- Plastic materials are subject to fracture resulting from point loading. For this reason the presence of stones and other similar materials in the surround media should be noted.
- Pitting concentrated at the crown of a ferrous pipe may be caused by rocks in the backfill damaging the external coating when the pipe was originally buried. Such effects are likely to occur wherever the system is in rocky soils (Dorn, 1996).

### F81.3 Application

This technique is used commonly onsite and should be undertaken whenever a pipe is exposed and as a precursor to other condition assessment techniques.

### F81.4 Practical considerations

- Visual inspection is a widely applied approach to condition assessment and can be applied by operators with a basic knowledge of asset deterioration.
- Standard inspection record forms should be used to ensure all relevant data are collected and is available in a standard format (Dorn, 1996). Training of maintenance/service personnel in the requirements of completing inspection forms can increase data available for analysis.
- Digital photographs can be taken to provide a permanent record of points of interest.

### F81.5 Advantages

- Physical observation can be conducted when the asset is exposed for other reasons enabling useful information to be obtained at minimal cost.

- The technique is simple and requires no specialized equipment, although a camera and welding hammer can be useful. When undertaken as an opportunistic inspection it is low cost. Results can be used to indicate any further tests which might be useful.

## F81.6 Limitations

- Results are qualitative only; depending on operator experience and detail included in inspection reports. Results are also limited to the section observed.

**Table F-83. Summary Visual Inspection (pipes).**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes. |
| | Material type | Any. |
| | Service Area | Wastewater and potable. |
| | Access requirements | Physical access to the asset is required. |
| | Limitations relating to asset condition | None. |
| | Limitations relating to asset size/geometry | None. |
| | Continuous/discrete | Results are discreet. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | Inspection does not affect assets. |
| Technical suitability | Assessment parameters | Visual condition of pipe, and quality of backfill. |
| | Integration with software tools | None. |
| | Commercialization of tool | Framework approach. |
| | Previous/existing use of the tool in sector | Widespread use. |
| | Accuracy/reliability | Qualitative only. |
| | Ease of validation of results | Results can be validated through other assessment techniques. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); useability | Operator training is required for consistent results. |
| | Technology required (level of tool sophistication) | None. |
| | Documentation | Technique described well in literature. |
| | Availability of technical support | Information available in literature. |
| Economic factors | Cost per inspection | Low cost. |
| | Resource requirements | Can be undertaken by a single person. |

## F81.7 Bibliography


1. Dingus, M., Haven, J. and Austin, R. *Non-destructive None Invasive Assessment of Underground Pipes*, AwwaRF, USA, 2002
2. Dorn, R., Howsam, P., Hyde, R.A. and Jarvis, M.A. *Water mains: Guidance on assessment and inspection techniques*, CIRIA Report 162, Construction Industry Research and Information Association, London, England, 1996
3. Rajani, B.; Kleiner, Y. *Non-destructive inspection techniques to determine structural distress indicators in water mains*, National Research Council of Canada, Institute for Research in Construction, NRCC-47068, 2004, (downloaded from www.nrc.ca/irc/ircpubs)

# F82.0 WARP

## F82.1 Overview

WARP is a software-based decision support tool that helps to model the deterioration rates of water mains and subsequently plan their renewal. To achieve this, WARP provides a number of functions, including the analysis of water main breakage patterns, short-term operational forecasting and long-term renewal planning.

Static factors affecting pipe failure rates (e.g., pipe material, diameter, soil) are considered through the grouping of water mains into relatively homogeneous groups. Historical failure patterns are assumed to govern the future behavior of the water mains. Based on this assumption, and with the appropriate economic and cost data, the future impact of various operational strategies can be computed.

The analysis of water main breakage patterns is undertaken in WARP accounting for time-dependent factors such as temperature, soil moisture (rainfall deficit), main replacement rates and cathodic protection strategies. The influence of each of these factors on pipe failure rate is quantified to identify the background deterioration rates of buried water mains.

The impact of various operational strategies on future failure rates can also be predicted.

## F82.2 Main Principles

WARP is a computer program developed at the National Research Council of Canada (NRC). The software is designed to integrate the use of several models developed at NRC into a decision support tool-box.

WARP considers three types of factors affecting water main breakage rates. The first is termed background ageing, which is a result of corrosion and other continuous deterioration processes. The second consists of cyclical environmental effects such as temperature and soil moisture. The third comprises operational factors such as water main replacement rates and the rate of cathodic protection retrofit. As such, the analysis undertaken in WARP includes the following:

- ***A multi-variate model*** to predict water main breaks; a general, multi-variate exponential model is used to consider time-dependent factors in predicting water main breaks. This model is applied to groups of water mains that are assumed homogeneous with respect to their deterioration rates.
- ***Impact of climate***: The breakage rate of buried pipes can be influenced by climatic conditions, in particular rainfall and frost. To incorporate climate, WARP uses a surrogate measure for the severity of winter in a given year. Similarly, a surrogate measure is used for soil moisture.
- ***Impact of cathodic protection strategies***; this module is used to allow the benefits of retrofitting cathodic protection to be incorporated into the analysis (cathodic protection is assumed to be fitted either opportunistically at the time of pipe failures, or in a systematic retrofitting program).

WARP can perform analyzes of historical breakage rates with or without any number of covariates. When no covariates are selected, the results indicate an average ageing rate only. When one or more covariates are selected, the results reflect background ageing (the consistent increase in pipe breakage rate due to corrosion and other continuous deterioration processes) as well as annual variations due to the influence of time-varying, dynamic factors.

Once the analysis identifies all the parameters and coefficients governing the breakage rates in the water mains, expected future breakage rates can be forecasted. With the appropriate economic data, such as costs of breakage consequences, pipe replacement and cathodic protection, long-term planning can then be undertaken.

WARP can perform some rudimentary optimizations as well as calculate the life-cycle costs of any user-defined strategy, which may include combinations of cathodic protection and pipe replacement over several years.

## F82.3 Application

The software is designed to facilitate rehabilitation planning and maintenance management of water distribution assets.

## F82.4 Practical considerations

- There has been limited use of the tool to date; through it has been developed with the in-kind support of water utilities in Canada and the United States.
- The software is Windows based and has a graphical user interface.
- Significant volumes of data are required for the application of the approaches to pipe failure prediction.

## F82.5 Advantages

- WARP integrates a number of tools into a decision support tool-box; the tools are based on published research.
- The analysis of both steady and dynamic influences on the pipe failure rate are considered, which will allow utilities to understand the background level of network deterioration without the influence of annual variations associated with dynamic factors beyond the utility's control.
- The tool allows various operational strategies to be considered to determine their relative effectiveness.

## F82.6 Limitations

- Use of tool to date has been limited to the development projects.
- Data requirements are high.
- Analysis is based on the assessment of asset cohorts. It is thus macro model that estimates a broad range of lengths of water mains to be rehabilitated or replaced each year. The model does not predict specific water mains that should be rehabilitated or replaced each year.

**Table F-84. Summary WARP.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Pipes, water pipeline infrastructure |
| | Granularity | System and asset cohorts. |
| | Service Area | Potable. |
| Technical suitability | Focus of analysis | Long-term asset management planning using asset failure curves developed from utility asset data. |
| | Scalability of tool/approach | Better suited to medium to large authorities where good asset data is available. |
| | Commercialization | Commercial software released in 2006. |
| | Previous/existing use of the tool | Developed through in kind support from utilities in the United States and Canada . |
| | Ease of validation | Initial validation is provided in statistical analysis of failure data and development of failure curves. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Potable; designed for system level, but does allow assessment at sub network level. |
| | Integration with other tools/GIS | None. |
| Utility technical capacity | Asset management sophistication | Aimed at higher level of asset management where good asset data is available. |
| | In-house skills required | Asset manager/engineer. |
| | Technology required | PC based tool. Windows based operating system. |
| | Documentation | Research and development fully documented. |
| | Data Requirements | Good quality asset data and asset failure history data is required. |
| | Linking to asset data | None; cohort level analysis. |
| | Availability of software and technical support | Software available through NRC. |
| | Usability | Simple user interface. |

## F82.7 Bibliography


1. Kleiner, Y.; Rajani, B. *Modeling the deterioration of water mains and planning their renewal*, National Research Council of Canada, Institute for Research in Construction, NRCC-46119, 2002 (downloaded from www.nrc.ca/irc/ircpubs)
2. Rajani, B.B.; Kleiner, Y. *WARP - water mains renewal planner*, National Research Council of Canada, Institute for Research in Construction, NRCC-44680, 2001 (downloaded from www.nrc.ca/irc/ircpubs)

## F83.0 WRc Sewer Rehabilitation Manual

### F83.1 Overview

The WRc Sewer Rehabilitation Manual (SRM) is a framework for assessing the condition and performance of sewerage networks. The SRM sets out a strategy that concentrates appropriate investigations on those parts of the system where problems are most severe with the aim of producing:

- Significant cost savings in necessary rehabilitation works.
- The ability to limit future rehabilitation costs as the network gets older.
- The means of quantifying and justifying the financial requirements for future upgrading programs.

The approach was developed principally to meet the sewerage rehabilitation needs of the United Kingdom water sector. However, it has since been applied in a number of other countries. While it had an initial focus on the United Kingdom, some minor amendments were made to bring the SRM approach into line with the European Standard, *Drain and Sewer Systems Outside Buildings: Part 5 Rehabilitation*.

### F83.2 Main Principles

The SRM is currently divided into two volumes:

- ***Volume 1*** deals with the determination of the structural performance of sewers, survey techniques, and procedures for assessing deterioration and collapse mechanisms, analysis of hydraulic performance, and maintenance planning.
- ***Volume 2*** deals with new renovation techniques and structural design methods for sewer renovation.

The basis of the SRM procedure is the systematic investigation of drainage areas, so the division of the utility's area of operation into one or more drainage areas (catchments) is essential. The SRM procedure for a drainage area is divided into three main stages:

1. ***Initial Planning***: this is an initial investigation to establish the extent and type of problems in the drainage area and to plan the approach for the diagnostic study.
2. ***Diagnostic Study***: this is the detailed investigation stage, which is tailored to meet the needs of the drainage area. The details of the study therefore depend on the nature of the problems identified during the initial planning stage.
3. ***Implementation***: the final stage of the procedure involves the implementation of the rehabilitation plan, operation of the system in accordance with the operations and maintenance plan, and the long term monitoring of the system.

A key aspect of the diagnostic study is the structural condition assessment of the sewers, which is achieved through standard CCTV inspection and grading procedures. Selection of sewers to inspect is targeted towards those sewers where the risk of failure is highest. The types of failure considered can include one or more of the following:

- Structural collapse of the sewer.
- Blockage of the sewer.
- Leakage of effluent from the sewer.

Without first inspecting the sewers it is not possible to fully assess the risk of failure. Three possible approaches are described in the SRM to address this paradox:

1. **Consider only the consequences of failure.** Since the assessment of the consequences of failure does not generally depend on the condition, consequence can be used as a basis for identifying potentially high risk sewers. A method of identifying those sewers (termed **critical sewers**) with a high consequence of collapse is a central feature of the SRM. The consequences include direct costs to the utility as well as social costs (e.g., traffic disruption).
2. **Consider available information known to affect the likelihood of failure.** This approach allows the selection of those sewers where other factors would suggest that the likelihood of failure is high (e.g., shallow depth).
3. **Consider consequences together with the available information known to affect the likelihood of failure.** This approach allows the selection of sewers with high failure risk, whether this is due to the high consequences failure, a high likelihood of failure, or a combination of both.

When considering which sewers to inspect, the principle aim is to select a group such that the total costs of failure over time would be significantly higher than the costs of inspection and subsequent pro-active rehabilitation before failure. In some countries, legislation requires inspection of certain sewers. If this is the case, this requirement will override any other consideration.

After CCTV inspection, each sewer length inspected is assigned into one of five grades as set out in Table F-85. Two methods of assessing the internal condition grade are available:

- A computerized scoring system based on defect codes.
- A manual method.

**Table F-85. Internal Condition Grades.**

| Grade | Implication |
|---|---|
| 5 | Collapsed or collapse imminent. |
| 4 | Collapse likely in foreseeable future. |
| 3 | Collapse unlikely in near future but further deterioration likely. |
| 2 | Minimal collapse likelihood in short term but potential for further deterioration. |
| 1 | Acceptable structural condition. |

Once the internal condition grade has been allocated, various other factors are used to make an assessment of the likelihood of structural failure (collapse) of the sewer or further deterioration. To this end, a structural performance grade (SPG) is allocated based on the internal structural condition grade and other information such as surcharge potential and soil type.

***Since an internal structural condition of (say) 3 (collapse unlikely in near future but further deterioration likely) can represent low or high risk depending on the specific asset's context, it is the SPG that is of most interest to the asset manager.***

## F83.3 Application

The SRM provides guidelines and procedures to assist in the planning and design of works to improve the performance of existing sewer systems and in the strategic planning of operations and maintenance work.

## F83.4 Practical considerations

- The SRM is published as a CD and can be purchased from WRc (http://www.webookshop.com/). A trimmed down version of the manual can be found at http://www.wrcplc.co.uk/srm/.
- The manual has been widely adopted in the United Kingdom and is also used in other countries.
- While the scope of the manual is focused on wider service issues, structural condition is a major focus of the SRM approach and is assessed through the collection and interpretation of CCTV and other data.

## F83.5 Advantages

- The WRc framework is a generic approach built on a well established engineering framework. As such it provides a practical means of collecting information to better understand the condition and performance of sewerage networks.
- The WRc approach can be used to obtain both an understanding of present condition and the interventions required to address service issues in sewerage networks.

## F83.6 Limitations

- The overall approach has been designed in light of European practices; United States approaches may differ from those adopted.
- The approach presupposes there are issues within the drainage area. Drainage areas that do not have hydraulic, environmental, structural or operational problems are outside the applicability of the SRM and do not warrant investigation in the manner described in the Manual. As such, the scope of the SRM does not cover drainage areas where there are no service issues.

**Table F-86. Summary WRc Sewer Rehabilitation Manual.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Sewerage networks. |
| | Granularity | Drainage area to sewer level. |
| | Service Area | Wastewater |
| Technical suitability | Focus of analysis | Cost effective management of sewerage assets; resolution of service problems in drainage areas. |
| | Scalability of tool/approach | Scaleable; framework can be tailored to meet the demands of any size company. |
| | Commercialization | Framework available as a manual. |
| | Previous/existing use of the tool | Has been widely used in the United Kingdom water sector. |
| | Ease of validation | Validity of results depends on data collection and interpretation. |
| | Flexibility with analysis (asset types) and granularity (system, asset level) | Wastewater; asset to system level. |
| | Integration with other tools/GIS | N/A |
| Utility technical capacity | Asset management sophistication | Generic approach. |
| | In-house skills required | Professional engineering skills required for development of assessment program. Contractors usually used to inspect pipes |
| | Technology required | Depends on CCTV inspection tool used. |
| | Documentation | Approach documented in a Manual that has been kept current and up to date. |
| | Data Requirements | High; requires data on drainage area and environment, but the program can be tailored in terms of affordability issues. |
| | Linking to asset data | N/A |
| | Availability of software and technical support | Not supported by software. Technical support is not available except on a consultancy basis. |
| | Usability | N/A |

## F83.7 Bibliography


1. WRc (2001) S*ewerage Rehabilitation Manual – 4th Edition*, Water Research Council (WRc), Accessed October 2006 (Limited content version): http://www.wrcplc.co.uk/srm/

## F84.0 WRc Trunk Main Structural Condition Assessment Approach

### F84.1 Overview

The WRc Trunk Main Structural Condition Assessment approach is a framework for assessing the structural condition of large diameter pressure pipes. It can be applied to the range of pipe materials used in the bulk transmission of potable water; that is, ferrous, cementitious, and plastics. The approach also covers the condition assessment of valves.

The overall approach is broken down into a number of logical steps:

- ***Initial Data Gathering***: Define the purpose of the study, and review currently available (including opportunistic) data.
- ***Subdivision of system*** under study into categories on the basis of physical pipeline features and environmental factors.
- ***Inspection of pipes*** in the categories of importance, with due consideration given to factors such as the strategic importance of the pipe, the consequence of pipe failure and known problem pipes/areas.
- ***Analysis and interpretation of data***.

### F84.2 Main Principles

The basic purpose of WRc's structural condition assessment framework is to draw general conclusions about the current and future structural condition of the system under study from a limited number of discrete observations made at a fixed point in time. To achieve this, the pipeline system to be assessed is notionally divided into categories based on pipe parameters and environmental factors. The pipe parameters and environmental factors include such things as:

- Pipe diameter.
- Corrosion protection systems.
- Soil type and characteristics.
- Water source and composition.

Other categories are added covering such things as valves, pipe bridges, etc.

Once the pipeline system has been appropriately divided, an inspection program is then developed to cover the asset categories identified. These inspections provide a snapshot of the current state of the system. To be able to provide future predictions of asset condition, information on the following is also required:

- The deterioration mechanism.
- The deterioration rate.
- The change of the deterioration rate over time.
- The point in the deterioration process at which the pipe fails.

### F84.3 Application

A framework approach to the condition assessment of large diameter transmission pipes.

## F84.4 Practical considerations

- The WRc approach to condition assessment is detailed in a published manual obtainable from WRc (http://www.webookshop.com/index.asp).
- In practice, the WRc approach has often been applied to the assessment of cast iron pipes. For these pipes, measurement of condition is often made by shot blasting the pipe, measuring external pit depths by manual means (e.g., using a welding gauge), and use of ultrasonic sensors to assess the level of internal pitting. Remaining life is then calculated through simplifying assumptions, namely that:

  1. Corrosion is assumed to be initiated as soon as the pipe is brought into service;
  2. The internal and external corrosion rates do not change with time;
  3. The deepest external pit measured is coincident with the calculated deepest internal pit, that is, maximum thinning of the wall, based on measured values, is assumed;
  4. The 'failure' of the pipe is taken to occur as soon as corrosion penetrates the wall, so called through-wall corrosion.

- These simplifying assumptions mean there is a high degree of uncertainty inherent in the predictive assessment of structural condition in the future. The WRc manual notes that it is important that this uncertainty is taken into account when interpreting survey results so that appropriate management decisions can be made.
- Where the variability in structural condition within the system is low, and observation points are well chosen, the WRc approach will allow conclusions to be drawn about the system-wide condition. As the variability increases, however, the number of observation sites required to accurately quantify that variability increases, and it becomes difficult to provide accurate information about the state of the overall system. It is thus critical to precisely define the objectives of a study so that a cost-effective assessment program with an appropriate level of discrimination can be devised.
- Brittle failures are often independent of pipe deterioration; the condition of valves is therefore important to damage limitation.

## F84.5 Advantages

- The WRc framework is a generic approach built on a well-established engineering framework. As such it provides a practical means of collecting information to better understand the condition of large diameter pipes.
- The WRc approach can be used to obtain both an understanding of present condition and, with the application of appropriate simplifications, the change in condition into the future.

## F84.6 Limitations

- Having been first published in 1992, the approach could be considered somewhat dated, especially with regard to the use of discrete sampling techniques. However, in practice the underlying principles are still valid and pragmatic in many situations, especially for utilities with little information regarding their transmission pipe network.
- The main limitation of the approach is that generalized conclusions are made about pipeline systems from measurements made at a limited number of discrete points.

- The WRc Manual notes that the confidence levels of the asset life predictions are low and should be interpreted accordingly. In particular, predictions of asset life expectancy do not indicate the time to next failure.

**Table F-87. Summary WRc Trunk Main Structural Condition Assessment Approach.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Trunk mains; pipes and valves. |
| | Granularity | Pipelines or networks of pipes. |
| | Service Area | Potable. |
| Technical suitability | Focus of analysis | Current structural condition and remaining life |
| | Scalability of tool/approach | Scaleable; inspection program can be tailored to meet the demands of any size company. |
| | Commercialization | Framework available as a manual. |
| | Previous/existing use of the tool | Has been widely used in the United Kingdom water sector. |
| | Ease of validation | Results of discrete sampling procedures are uncertain. |
| | Flexibility with regard to analysis (asset types) and granularity (system, asset level) | Mainly potable, but applicable to force sewer mains; asset to system level. |
| | Integration with other tools/GIS | N/A |
| Utility technical capacity | Asset management sophistication | Generic approach. |
| | In-house skills required | Professional engineering skills required for development of assessment program. Contractors usually used to inspect pipes. |
| | Technology required | Depends on inspection tool used. |
| | Documentation | Approach documented in a manual, though this is somewhat out of date, the underlying principles still apply. |
| | Data requirements | Moderate; requires data on pipeline and environment, but the program can be tailored in terms of affordability issues. |
| | Linking to asset data | N/A |
| | Availability of software and technical support | Not supported by software. Technical support is not available except on a consultancy basis. |
| | Usability | N/A |

## F84.7 Bibliography

1. Randall-Smith, M., Russell, A. and Oliphant, R. *Guidance manual for the structural condition assessment of trunk mains*, WRc, United Kingdom, 1992

## F85.0 Volumetric X-Ray or Radiographic Testing

### F85.1 Overview of Tool

Volumetric X-Ray or radiographic testing is a non-destructive method used for checking the integrity of metal assets such as welded pipe joints and plant components.

The technique is based on the transmission of X-rays onto to an object, with the resultant radiation signal being used to produce an image. Volumetric X-ray testing uses multiple X-ray images taken from different angles to enable reconstruction of any horizontal or vertical X-ray image plane. This capability enables the viewing of additional information that may be hidden by obstructing details in the testing region of interest (Berger and Schulte, 2002). This can assist in providing additional information for the detection and characterization of discontinuities, such as hollow spaces or foreign material, in all kinds of structures, including welds, castings, electronic devices and electromechanical assemblies.

### F85.2 Main Principles

Volumetric X-ray testing requires a minimum of two images to be taken from different angles in order to permit the viewing of stereo images. A typical testing set-up is shown in Figure F-15. The X-ray source is located at an oblique angle with respect to the vertical direction of the object (asset component). The object under test is rotated to eight different positions, and an X-ray image is taken at each position. The process is very flexible and is not constrained to any specific positions, number of images or geometry. The circular image pattern, however, is convenient to demonstrate the technique. The image detector can be any flat panel detector, film or scintillator.

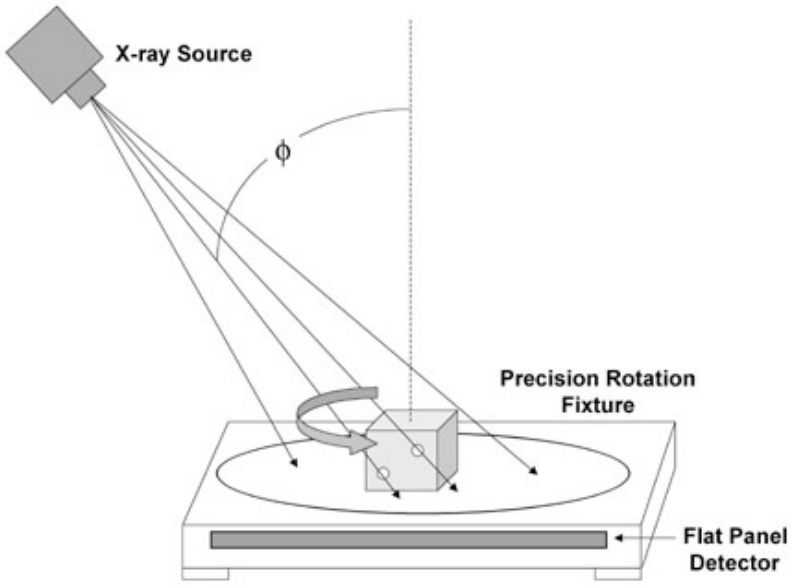


**Figure F-15. Volumetric X-Ray Testing**
**(Reprinted with permission from: The American Society of Nondestructive Testing, 2002).**

Any view through the object can be reconstructed with software tools that use the basic set of oblique incidence images acquired during the X-ray test to develop an image. The reconstructed X-ray image planes have the capacity to provide precision dimensional measurements.

Horizontal and vertical X-ray reconstructed images can provide excellent location information about weld discontinuities. Information about discontinuities such as the size and location of pores and inclusions in the weld bead can be reconstructed along the direction of the weld and through the center of the pore. By combining this with the capability for dimensional measurement, the quality of the weld can be assessed and repair decisions such as from which side of the weld to start can be made.

## F85.3 Application

X-ray tomosynthetic imaging (imaging by sections or sectioning) can be used on a wide variety of assets including castings, electronic devices and electromechanical assemblies; however the most practical application for the water industry is weld testing. The following standards reference this test method:

- ASME Code 31.1 and B31.3 standards are applicable for pressure vessels.
- AS 3507.1—2003 Non-destructive testing Part 1: Guide to radiography for ferrous castings.

Tomography (imaging by sections or sectioning) is defined in ASTM E-1316 (1999).

## F85.4 Practical Considerations

- Volumetric X-ray testing is a commonly used non-destructive testing method outside of the water industry. Equipment for industrial application, such as inspection of welds, is commercially available from a large number of suppliers. The equipment can be supplied in a number of configurations from portable units that can be used in the field by one operator to larger non-portable units.
- Volumetric X-ray testing has to be carried out by trained staff aware of all the health and safety issues involved in the use of ionizing radiation. In addition, experience is required to interpret the radiographs produced.
- Accurate interpretation of volumetric X-ray images requires skilled operators who can recognize and categorize the flaws in welded joints. Zuev et al (2006) propose the following main types of defects that can be observed in welded joints using X-ray testing: pores, slag or tungsten inclusions, incomplete fusions and cracks.
- Access is often required to both sides of asset or asset element, which is not always practical. When an X-ray source is placed on one side of the asset and a photographic plate which records the image is placed on the other, safety precautions are required to safeguard personnel and the general public. This procedure is usually expensive and the disruption often unacceptable for routine investigations.

## F85.5 Advantages

- Use of a digital flat panel provides high sensitivity, fast response and good resolution. Images of any region of an asset can be obtained quickly and with little effort with volumetric X-ray systems. The viewer can look behind obstructing details that may hide the region of interest.
- Reconstructed viewing of any horizontal or vertical X-ray image plane is achievable along with the ability to scan through selected horizontal or vertical image regions as well as a precision measurement capability. Volumetric X-ray imaging in conjunction with methods such as tomosynthesis or computed tomography can provide the additional information often needed for critical non-destructive testing applications.

- Volumetric X-ray imaging's real-time radioscopic capability means that an immediate response is given during testing. The operator can view the usual two dimensional X-ray image and decide if more information is needed to complete the test. If that is the case, additional images can be taken while the asset to be tested is in place to provide the volumetric images needed.

## F85.6 Limitations

- Volumetric X-ray imaging is relatively time consuming and expensive. There are also significant occupational safety hazards associated with the use of X-ray imagery due to the potential for radiation accidents. The staff operating the equipment need to be fully trained in safe operating procedures and monitored for radiation exposure.
- The accurate development and interpretation of volumetric X-ray testing to identify asset defects requires significant operator experience and expertise.

**Table F-88. Summary Volumetric X-Ray or Radiographic Testing.**

| | Criteria | Assessment |
|---|---|---|
| Technical selection | Assets covered | Welded pipe joints, castings, electronic devices, electromechanical assemblies and other plant components. |
| | Material type | N/A |
| | Service area | Potable and wastewater. |
| | Access requirements | None. |
| | Limitations relating to asset condition | No restriction. |
| | Limitations relating to asset size/geometry | No limitations relating to size of element. |
| | Continuous/discrete | Continuous reading in time and space. |
| | Destructive/non destructive | Non-destructive. |
| | Interruption to supply/function | The asset will be required to be taken off-line if asset components are taken for laboratory testing or access is required by testing apparatus from the water side of asset. |
| Technical suitability | Assessment parameters | The measurement, detection and characterization of asset components. |
| | Integration with software tools | Stand alone. |
| | Commercialization of tool | Equipment is fully developed, available from selected commercial vendors. |
| | Previous/existing use of the tool in sector | Widespread use internationally on steel bridges, in the petrochemical, process and nuclear industries. Relatively common selective applications in the water industry, e.g., on pipework. |
| | Accuracy/reliability | Quantitative. Accuracy is dependent on the resolution of the image detector. |
| | Ease of validation of results | Direct measurement. |
| Utility technical capacity | Asset management sophistication required | Generic approach. |
| | Skills required (level of tool sophistication); useability | Trained staff can take measurements. Limited specialist knowledge and training required. |
| | Technology required (level of tool sophistication) | High level of sophistication. |
| | Documentation | AS 3507.1—2003. |
| | Availability of technical support | Technical support available from distributors. |
| Economic factors | Cost per inspection | Relatively high cost per inspection. |
| | Resource requirements | One operator required. |

## F85.7 Bibliography


1. AS 3507.1 (2003) Non-destructive testing Part 1: Guide to radiography for ferrous castings
2. ASTM E-1316 (1999), Standard Terminology for Nondestructive Examinations.
3. Berger and Schulte *Volumetric X-Ray Testing, Back to Basics Archive* (Available at: http://www.asnt.org/publications/materialseval/basicsarchive.htm), The American Society for Non-Destructive Testing, 2002
4. Zuev, V. M., Ivanov, V. I. and Kapustin, V. I. *Classification of flaws in ultrasonic and X-ray testing*, Russian Journal of Nondestructive Testing, Vol. 42, No. 5, pp. 325-333, 2006